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Quality Driven Scheduling in Construction



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Quality Driven Scheduling in Construction

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Abstract

Despite the enormous research effort that has been made in the last fifty years, the goal of construction scheduling quality seems still a long way far. This dissertation has the aim of contributing to the understanding of the quality of construction scheduling, and three issues have been chosen: schedule quality; quality and project control; scheduling approaches for construction. The goal of the whole research work is to study quality in scheduling and project controlling, and to propose some possible research lines to better understand the needed quality for the planning, scheduling, and controlling approaches in construction projects, i.e. quality driven scheduling.

Starting from the development of the Critical Path Method (CPM), PERT and Precedence Diagramming, until the recent Location-Based Planning, project scheduling has been developing and improving continuously. However, construction project scheduling systems are still considered to miss the goal of increasing project control efficiency. Project Scheduling is, indeed, one of the basic tools of construction project management, and the success of a project partially depends on having a high quality schedule that defines when each activity will occur and with which duration, and its logic links with other activities and their sequences. Moreover, construction productivity is considered to be improved through scheduling as it can manage different problems such as process productivity, coordination and safety, and connections between systems and processes. Quality of construction scheduling has been object of research in a rather limited manner, and the need of recommended schedule development practices for quality assurance of scheduling processes and deliverables still exists. Therefore, the research work is based upon three main research questions: a) what is schedule quality? b) what does scheduling produce in terms of quality? c) can the activity network schedule model be process-oriented and quality driven? The gained results propose the following regarding to the research questions.

- a) What is schedule quality? Schedule quality is the fulfilment of many schedule requirements, with the aim of satisfying the needs of work structuring of construction process and of scheduling mechanics. A method of understanding and measuring schedule quality in construction, termed "Schedule Health Assessment" is proposed. The Schedule Health Assessment method also has the aim of guiding the project scheduler in the schedule development process.
- b) What does scheduling produce in terms of quality? Project schedule is the basis for project control, mostly addressing time and progress of activities, and costs, while quality control is usually separated. Although, these three project objectives are interdependent, and process and product quality management should be fully included in project control. Quality control should be integrated in the project schedule through a "Quality Breakdown Structure".
- c) Can the activity network schedule model be process-oriented and quality driven? Activity network creates logic of work structuring. A process-oriented scheduling method for construction has to deal with resources, workflow and spaces. The proposed method, termed Repetitive Networking Technique (REPNET), creates a quality driven construction-oriented schedule model by plotting network logic on resource-space charts and on flowlines.

The research results suggest the implementation of these three approaches in the project scheduling of a construction project can improve the quality driven scheduling of the project, meaning the implementation of a good quality schedule, the integration in project control processes of the delivered quality and the process-oriented scheduling.

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Papers included in the dissertation

This doctoral dissertation consists of a summary and of the following eight scientific publications, which are referred to in the main text using the following Roman numerals

Paper I

M. Bragadin, K. Kähkönen (2013). Innovation in Construction Project Control. Proceedings of ISTE 2013 Conference "ICT, Automation and the Industry of the Built Environment: from the Information Exchange to the Field Management" Politecnico di Milano, October 3rd – 4th, Milan Italy, Maggioli S.p.A. pp. 138-157. ISBN 88-387-6258-1

Paper II

M. Bragadin, K. Kähkönen (2013). Quality Evaluation of Construction Activities for Project Control. Journal of Frontiers in Construction Engineering vol.2 Issue 1 March 2013, pp. 17-24. ISSN 2306-7713 /2306-7721

Paper III

M. Bragadin, K. Kähkönen (2013). Repnet: Project Scheduling and Workflow Optimization for Construction Projects. Construction Management workshop proceedings, Department of Architecture, University of Bologna, Ravenna Campus, October, 17th -18th Ravenna Italy. IN_BO Ricerche e progetti per il territorio, la città e l'architettura, Special Issue no. 2/2013, pp. 17-28. ISSN 2036-1602

Paper IV

M. Bragadin, K. Kähkönen (2014). Schedule Health Assessment for Construction Projects. Proceedings of the ICEC 2014 – IX World Congress – Re-Engineering Total Cost Management, October 20th-22th Milan, Italy. ISBN 978-88-940141-0-5

Paper V

M. Bragadin, K. Kähkönen (2015). Safety, Space and Structure Quality Requirements in Construction Scheduling. Proceedings of the 8th Nordic Conference on Construction Economics and Organization, May 27th – 29th, 2015, Tampere, Finland. Procedia Economics and Finance 21 (2015) pp. 407-414. ISSN 2212-5671

Paper VI

M. Bragadin, K. Kähkönen (2016). Resource – Space Charts for Construction Work Space Scheduling. Proceedings of the CIB World Building Congress 2016 Intelligent Built Environment for Life (vol. III), May 30 – June 3, 2016, Tampere, Finland. Tampere University of Technology. Report 18. pp. 677-688. ISBN 978-952-15-3743-1

Paper VII

M. Bragadin, K. Kähkönen (2016). A Planning and Scheduling Paradigm for Construction Strategy of a Building Rehabilitation Project. Proceedings of ISTE 2016 Conference "Back to 4.0: Rethinking the Digital Construction Industry", June 30 – July 1, 2016, Naples, Italy, Maggioli S.p.A. pp. 238-247 ISBN 978-88-916-1807-8

Paper VIII

M. Bragadin, K. Kähkönen (2016). Schedule Health Assessment of Construction Projects, Construction Management and Economics, 34:12, pp. 875-897. doi:10.1080/01446193.2016.1205751. ISSN 0144-6193 (print) 1466-433X (online)

Author's contribution in the papers

The author of this dissertation was responsible for initiating, doing the research for and writing all the included papers. Professor Kähkönen provided valuable comments and suggestions to improve the papers. In particular, Professor Kähkönen gave the idea for the development of papers IV and VIII.

List of key terms and concepts

Construction Project Schedule. An output of the scheduling process for a construction project that presents linked activities with planned dates, durations, milestones and resources. (modified from PMI, 2013)

Construction Project Scheduling. Scheduling a construction project is the process used to determine the overall project duration and when activities and events are planned to happen, producing a construction schedule as an output. (modified from APM, 2016).

Critical Path Method (CPM). A method used to estimate the minimum project duration and determine the amount of scheduling flexibility on the logical network paths within the schedule model (PMI; 2013).

Flowline. A flowline chart of schedule information where locations of the project are listed on the vertical axis, dates are shown on the horizontal axis and activities are shown as lines plotted on the chart, according to start and finish dates and start and finish locations where work is performed by resources.

Gantt Chart. A bar chart of schedule information where activities are listed on the vertical axis, dates are shown on the horizontal axis, and activity duration are shown as horizontal bars placed according to start and finish dates (PMI, 2013).

Key Performance Indicators (KPIs). Measures of success that can be used throughout the project to ensure that its progressing towards a successful conclusion (APM, 2016).

Precedence Diagramming Method (PDM). A technique used for constructing a schedule model in which activities are represented by nodes and are graphically linked by one or more logical relationship to show the sequence in which the activities are to be performed.

Project Control. Project control is based on project objectives, plans and contracts. It measures actual progress and performance, compares against the baseline, and takes any necessary remedial action (IPMA, 2006).

Project Management. The application of knowledge, skills, tools, and techniques to project activities to meet project requirements (PMI, 2013).

Quality. The degree to which a set of inherent characteristics of an object fulfils requirements, where a requirement is a need or expectation that is stated, or generally implied or obligatory. Quality is the level of accomplishment of product and processes to performance requirements (ISO 9000:2015).

Quality Breakdown Structure (QBS). A hierarchical decomposition of the total quality of work to be carried out by the project team to accomplish the project objectives and create the required deliverables (modified from PMI, 2013).

Repetitive Networking Technique (REPNET). An heuristic procedure for resource/space oriented construction project scheduling. REPNET is based upon a precedence network plotted on a resource–space chart and a flowline view.

Schedule Quality. The degree to which a scheduling process and a schedule fulfil the requested requirements. Schedule quality entails quality of scheduling process and of scheduling output, the schedule itself.

Schedule Management. Is the process of developing, maintaining and communicating schedules for time and resource (APM, 2016 website)

Schedule Model. A representation of the plan for executing the project's activities including durations, dependencies, and other planning information, used to produce a project schedule along with other scheduling artefacts (PMI, 2013).

Schedule network diagram. A topological representation of the project showing logical relationships among activities.

Schedule Health Assessment. A method to perform the quality assessment of a construction schedule, based upon seventy-five requirements grouped into five measurement Indicators. The method can also be used as guidance in the development of a quality schedule by project schedulers.

Work Breakdown Structure (WBS). A hierarchical decomposition of the total scope of work to be carried out by the project team to accomplish the project objectives and create the required deliverables (PMI, 2013).

Work Structuring. Lean work structuring is process design integrated with product design to deliver a project (Ballard, 1999).

Table of Contents of the dissertation

Acknowledgments

Papers included in the dissertation

List of key terms and concepts

1. Introduction	13
1.1 Motivation and research context.....	13
1.1.1 Project management: roots, core processes and construction projects	13
1.1.2 Planning and scheduling approaches for construction projects	15
1.1.3 The schedule quality.....	19
1.2 Research Design.....	21
1.2.1 Research objectives.....	21
1.2.2 Research questions	22
1.3 Research methodology.....	24
1.3.1 Research context.....	24
1.3.2 The research method	24
1.3.3 Research methods and approaches of the appended papers	26
1.4. Research structure	29
1.4.1. Work Pack #1 Construction schedule quality.....	29
1.4.2. Work Pack # 2 Construction quality in project control	30
1.4.3. Work Pack # 3 Construction scheduling proposed method	30
1.4.4 Research structure: appended papers	33
2. Theoretical foundation.....	35
2.1 Introduction: project planning, scheduling and control systems for construction.....	35
2.1.1 Project planning and scheduling in construction.....	35
2.1.2 Control systems for construction	36
2.1.3 Construction scheduling & process modelling.....	38
2.1.4 Safety management and project management.....	41
2.1.5 Quality of construction schedules and scheduling phases	43

2.1.6 Health and safety-oriented construction schedules.....	47
2.2 Previous research.....	49
2.2.1 Schedule quality for construction projects	49
2.2.2 Construction quality approach in Project Control.....	57
2.2.3 Scheduling approaches for Construction Projects: a criticism of the activity network approach	61
2.3 Summary of the previous research and its limits.....	67
2.4 Aim of the dissertation.....	68
3. Summaries of the papers	70
3.1 Paper I: Innovation in Construction Project Control	70
3.2 Paper II: Quality Evaluation of Construction Activities for Project Control.....	72
3.3 Paper III: REPNET: Project Scheduling and Workflow Optimization for Construction Projects.....	75
3.4 Paper IV: Schedule Health Assessment for Construction Projects	78
3.5 Paper V: Safety, Space and Structure Quality Requirements in Construction Scheduling.....	81
3.6 Paper VI: Resource – Space Charts for Construction Work Space Scheduling	84
3.7 Paper VII: A Planning and Scheduling Paradigm for Construction Strategy of a Building Rehabilitation Project	87
3.8 Paper VIII: Schedule Health Assessment of Construction Projects	90
4. Discussions	93
4.1 Discussion of the contributions of the research	93
4.2 Improved understanding of the schedule quality (RQ #1)	96
4.3 Scheduling as a quality creation function (RQ #2)	98
4.4 Resource – space charts as means for improving activity network schedule quality (RQ#3)	100
4.4.1 The development of the REPNET - Repetitive Networking Technique	100
4.4.2 Comparison between REPNET and existing methods	101
4.5 Summary of the discussion of contributions of the research	105
5. Conclusions	107
5.1 Summary of the results	107
5.1.1 Contributions of the research	108
5.2 Evaluation of the research.....	110
5.3 Limitations of the research.....	111
5.4 Future research.....	112

References114

Annexes124

 Appended papers I - VIII.....124

1. Introduction

1.1 Motivation and research context

1.1.1 Project management: roots, core processes and construction projects

Planning, scheduling and controlling systems occupy a central position in the functions of a construction project manager. The challenges of project management are numerous, but organization, time and resourcing projects have been considered by project managers as major problems in the delivery of projects (Hussain, Wearne, 2005). In the last fifty years managing a project has become an art and a science, a profession indeed. . Project Management knowledge is defined by specific code of practices, bodies of knowledge and competence baselines, being the objective of a world-wide effort of thousands of research works. Nevertheless, projects continue to suffer problems of achieving their promised delivery, quality and cost, especially in the construction sector.

Much research and development effort has been made in this direction, and many intellectual roots of project management research have been discovered (Söderlund, 2004). The first and the most important seems to have its origins in the various types of planning and scheduling techniques, such as Gantt chart, CPM, PERT and Precedence Diagramming (Gantt, 1919, Moder, Phillips and Davis, 1983; Wren and Bedian, 2009). Beside this, project management has its origins also in temporary organizational forms (Lundin, Söderholm, 1995). Two different bodies of knowledge seem to be the intellectual roots of project management. The first is engineering science and applied mathematics, primarily interested in planning and scheduling techniques and methods of project management. This line of research would indicate project management as a specific problem-solving method based on project activities' understanding, grouping, planning, scheduling and controlling. The second has its intellectual roots in the social sciences, such as sociology, organization theory and psychology, and it is primarily interested in the organizational and behavioural aspects of project organizations and in organizational theories. Nevertheless, in the end, it is believed that projects are nothing else than a way of looking at industrial and organizational activity (Söderlund, 2004). Consequently, research into project management can follow one of these two lines, or both. It is a matter of trying to capture the "unique, complex and time-limited processes of interaction, organization and management" (Söderlund, 2004).

Also, the conceptualization of project management theories by Koskela and Howell (2002) divides the Project Management Body of Knowledge (PMBOK) mainly in two parts, the project theory and the management theory, but the viewpoint is process classification.

The project theory is based upon scope management through managing the needed work. This means that the work needed to achieve project objectives can be managed by decomposing the total work effort into smaller parts, namely activities and tasks, as represented in the Work Breakdown Structure (WBS). The WBS defines the project scope and its components termed Work Packages, that are related by sequential dependencies. These processes, according to the PMBOK guide (PMI, 2013) are the product-oriented processes. The management theory is based upon five process groups: initiating, planning, executing (or implementing), controlling and closing; these five processes group the project management oriented processes (ISO 2012; PMI, 2013). Planning, executing/implementing and controlling are the core project management processes meaning that planning processes provide a plan that is realised by the executing or implementing processes, and controlling processes detect variances from the baseline or requests for

changes, which lead to corrections in plans and executing processes (fig. 1.1). These core processes form a closed loop in perfect analogy with the Plan-Do-Check-Act (PDCA) circle of Deming (1982) as discussed later on in this dissertation. According to the PMBOK guide (PMI, 2013) and the ISO 21500 standard “Guidance on Project Management” these are the basic project management processes. The planning processes are considered of capital importance in the guides, and the scheduling development process is the main process of the planning group. .

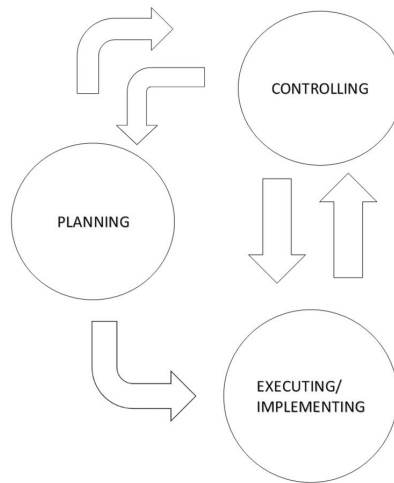


Figure 1.1: Core project management processes (ISO 21500).

The construction industry can be seen as an early source of specific processes of project management. Indeed, the practices of project management of construction projects were one of the foundations of the original 1987 guide to the Project Management Body of Knowledge (PMI, 2003), but the growing awareness of the values of project management to all kinds of projects and industries has led to the generalisation of concepts. Therefore, international standards like ISO 21500 and existing guidances of the Project Management Body of Knowledge issued by different related associations often do not cover all the present-day project management practices found worldwide in the construction industry.

Consequently, construction projects and their unique features should be defined related to the built environment modification processes, as the constructed environment is built through construction projects (PMI, 2003). Four types of construction projects can be detected: (1) residential construction; (2) building construction; (3) heavy engineering construction; (4) industrial construction. A construction project is a complex system in which resources (time, money, equipment, technology, information, people and materials) are organised into activities to be performed in a logical sequence (Barrie & Paulson, 1992). Construction projects' uniqueness is based upon the following specific features (PMI; 2003):

- only residential projects produce a product as such, on the contrary the generality of construction projects produce a facility, infrastructure, that will provide services, such as highways, dams and parks or house the means to make a product, material or immaterial;
- construction projects must deal with geographical differences and natural events;
- construction projects may have a significant impact on the natural and social environment by their very nature;
- they usually involve a team of hired specialists in design and construction disciplines;

- they involve many stakeholders, in particular public bodies and community groups;
- often require large amounts of capital investments, of materials and equipment.

Melles and Wamelink (1993) highlight that in construction industry satisfactory results of project management and control processes are not always found. This is because of the following characteristics of construction industry projects.

- A new production company, i.e. the construction site, is created for each construction order and exists for a short period time with temporary character;
- a large number of joint agreements (subcontracting, consortia) are arranged for a construction order;
- design activities (carried out by architects and engineers) and the production activities (carried out by the construction company) are not carried out by a single contractor.

These characteristics are unique to the construction industry. This means that the production control requirements and methods are different from other sectors of industry. In particular, the suitability of any given method of project management and control appears to be dependent upon the specific type of construction order (Melles, Wamelink, 1993).

Therefore, construction projects need a specific approach to project management as they have some generally accepted principles that are not common to all project types. The Construction Extension to the Project Management Body of Knowledge (PMI, 2003) says that the extension reflects unique or unusual aspects of the construction project environment, and common knowledge and practices that the project team must be aware of in order to manage the project efficiently and effectively.

In summary, the “engineering approach” to Project Management as defined by Söderlund (2004) has been chosen in the development of this dissertation, meaning the study of planning, scheduling and controlling techniques, that are considered core processes of the Project Management Body of Knowledge (Koskela and Howell, 2002). The study focuses on construction projects, and analyses the planning and scheduling techniques suitable for the construction sector. The aim of the dissertation is to study the characteristics of quality scheduling as this research effort originates from the search for a suitable method of creating a schedule model in the construction industry.

1.1.2 Planning and scheduling approaches for construction projects

The planning process is of paramount importance in the success of construction projects and project planning builds the foundations of several related functions, including estimating, scheduling, and project control. Planning involves the selection of the one method and sequence of work to be used on a project from among all the various methods and possible sequences, and provides detailed information for estimating, scheduling, and controlling. Scheduling is the determination of the timing of activities and follows the planning process. Many different methods of scheduling exists, bar charts, critical path methods, time-space charts like Line of Balance and flowline, and each one has its advantages and disadvantages (Callahan, Quackenbush, Rowings, 1992). Construction projects are complex entities that integrate different subsystems into a single product. One must bear in mind a product’s characteristics, resource organisation and contract constraints, and as a consequence, the large number of activities to perform creates a difficult scheduling environment. Because of this, and starting from the first development of the Critical Path Method (CPM), (Kelly, Walker, 1959), PERT (Malcolm, Roseboom, Clark and Fazar, 1959) and Precedence

Diagramming (Fondahl, 1962), construction – oriented project scheduling and control system has been the object of many research works. Although the methods and tools for project scheduling allow the project team to develop complete and accurate project models, project scheduling systems for construction are often still missing the goal of increasing project control and thus, project efficiency (Mecca, Naticchia, 1995). Project schedule should be an accurate project “roadmap” (PMI, 2007), that traces the path to reach project success and that tracks its achievements. But, unfortunately this goal is not often reached, and only the good will of project participants allows the achievement of project objectives and completion (Mecca, Naticchia, 1995).

Koskela (1992) claimed the need of new conceptualisation of the production philosophy of construction. The traditional conceptual model is associated to a conversion view of production that involves organisation and management processes. Production as a conversion model implies that the process is a set of activities that convert inputs to outputs. By focusing on conversions, the model does not consider physical flows between transformation processes. The new production model views production as a flow of material and / or information from raw material to the end product. In this flow, the material is processed, converted to output, inspected, waiting or moving. Processing represents the conversion aspect of production, inspecting, moving and waiting represents the flow aspect of production. The new conceptualization implies a dual view of production: it consists of conversions and flows. The overall efficiency of production is attributable to both the efficiency of the conversion activities performed, as well as the amount and efficiency of the flow activities through which the conversion activities are bound together (Koskela, 1992).

Following this production philosophy, Ballard and Howell (1998) proposed a new approach to production management in the streamline of this new production philosophy, claiming that in construction this new approach could be a driver of innovation following the example of the manufacturing industry. Production control consists of aggregate production planning, material coordination, workload control, work order release, and production unit control. Production control in construction implies to perform two different actions, planning and control. Planning is the production of budgets, schedules and other detailed specification of the production phases and constraints of the project, while control is the monitoring of the performance against those specifications, with corrective action as needed to conform performance to them. Instead, in manufacturing control is defined as the progressively more detailed shaping of material and information flows, i.e. the physical production process (Ballard and Howell, 1998). The proposed construction production control new approach consists of three hierarchical levels: initial planning, lookahead planning and commitment or weekly planning. Initial planning develops the project budgets and schedules providing a coordinating map that “pushes” completions and deliveries of construction. Lookahead planning develops material coordination plan and workload capacity studies, therefore “pulling” resources into the process. Commitment planning or weekly planning corresponds to work order release and production unit control, basing upon actual resources and their commitment to what will be produced (Ballard and Howell, 1998).

Later, Ballard (2000) proposed the Last Planner System of Production Control (LPS), building on this production control approach. Construction production can be conceived as a process of converting inputs to outputs, as a flow of materials through time and space, as a process for generating value for customers. All three conceptions are appropriate and necessary to understand production in construction. Production is understood as the processes of designing and making, and production management is composed of two phases, the planning phase and the execution or control phase. In the planning phase customer needs are determined and translated into design criteria, then work structuring is performed. Work structuring is defined as the process of activity identification, sequencing and scheduling. In the execution or control phase work flow control and production unit control are performed (Ballard, 2000). The Last Planner System has the aim of causing events to conform to plan, in opposition to the traditional project control process that basically aims at detect variances after-the-fact. The critique of traditional project controls in the AEC industry is that traditional controls do not deal with production management but only address cost and

schedule variances. Therefore, the Last Planner System focuses on workflow reliability to improve project cost and time performances mainly addressing social processes (Ballard, 2000).

Last Planner System has two components, production unit control and work flow control. Production unit control has the task of making better assignments to direct workers through continuous learning and corrective action, while the task of work flow control is to proactively cause work to flow across production units in the best achievable sequence and efficiency. The fundamental control indicator is the Percent Plan Complete (PPC), i.e. the number of planned activities completed divided by the total number of planned activities expressed as a percentage. Failure in achieving the planned production needs in deep analysis, and reasons of failure have to be identified and removed. Work flow control is defined by a hierarchy of plans and schedules, but lookahead planning is the core of the system. The lookahead schedule covers the next 3 to 12 weeks, entailing the current Weekly Work Plan. The lookahead schedule is based upon a barchart where work assignments are grouped by crews, and outstanding needs are specified. Once assignments are identified, constraint analysis is performed and bottlenecks are removed. LPS aims at creating a pull system of construction planning where materials and information are introduced in the production process only if the process is capable of doing that work. By contrast, traditional planning pushes inputs in the process based on target delivery or completion dates, seeking to cause resource to achieve planned objectives (Ballard, 2000).

This dissertation has its foundations in the wide line of research works about project scheduling of construction that bases its theories on the understanding of the different and complex needs of construction projects. Construction often consists of special types of complex projects that need a dedicated approach for scheduling. Regardless of the importance of social processes in construction, this dissertation aims at understanding quality of construction schedules with the previously mentioned “engineering” approach. The work by Kenley and Seppänen (2009; 2010) and its description of location-based scheduling techniques is the main reference and guiding light of this dissertation.

Location-Based Management System (LBMS) (Kenley, Seppänen, 2010), assumes that a project can be broken down into physical locations and planned and controlled on this basis. Tasks are assumed to flow through locations as locations stay fixed and can be easily monitored, tracking crew movement is more complicated. Logic is assumed to repeat in each location where the same tasks are performed, therefore simplifying the pattern of logic dependencies. Construction activities and tasks are better represented, planned, scheduled and controlled using time-space charts or flowlines. From this point of view and addressing lean production principles, the traditional Activity – based planning is not an appropriate planning system for construction projects (Koskela, 1992). Location-based system should be the natural planning systems that can solve the complexity of construction projects, as locations can be used to plan work flow continuity. The solution to the problem of coordinating trades is a location-based preplanning (Kenley, 2005).

Location-based Planning system has the following basic components (Seppänen, 2009):

- 1) Location Breakdown Structure (LBS). LBS is the core of the LBMS. LBS is organised hierarchically so that higher levels logically contain all lower levels of locations. The highest levels are based on the structural independence of building systems. The middle levels reflects physical constraints, building parts, floors. The lowest level are used for planning finishes and should contain only one trade in the work area.
- 2) Location-based quantities, tasks, and duration calculations. LBMS requires that quantities to be estimated based on the LBS. Location-based quantities are used to define the scope of work of each task. The quantities are used to compute task duration in each location.
- 3) Flowline. Flowline view is a time – space charts where tasks are plotted as diagonal lines versus time and locations. Location Breakdown Structure is on the vertical axis and the timeline on the horizontal axis. The workflow is displayed by the tasks plotted in each locations, and the slope of

the task indicates crew productivity. The locations with smaller quantities have a steeper slope assuming identical crew size.

- 4) Layered CPM logic. Location-based planning integrates CPM to flowline scheduling (Russell and Wong, 1993; Kähkönen, 1994; Suhail and Neale, 1994; Seppänen, 2009). Logic links between tasks in different location is termed “layered logic”. Layered logic automatically generates a PDM network based on locations. All four types of PDM logic links are possible (Finish to start, Start to Start, Finish to finish; Start to finish) and a lag can be imposed on logic relationships to delay the start/finish of the successor. Splitting of tasks is possible to form new subtasks in some locations.
- 5) Buffers (Goldratt, 2004; Rand, 2000; Steyn, 2000). The delay of the successor time can be also obtained with buffers to absorb contingencies. However, during implementation the buffer can be absorbed before affecting the succeeding trade, therefore the forecast ignores buffers when forecasting future problems. Buffers can be free locations (space buffers) or delay in logic links, any way in flowline view buffers can be seen as the horizontal and vertical empty spaces between two dependent tasks.
- 6) Risk Analysis. Risk analysis can be performed with Monte Carlo Simulation. Basing on risk analysis results some changes can be implemented, concerning the order of the locations, re-planning and rescheduling.
- 7) A CPM engine with continuity heuristics. Traditional CPM- based algorithm for times computation is available (Russell and Wong, 1993; Kähkönen, 1994; Suhail and Neale, 1994; Seppänen, 2009). The work can be planned to be continuous or discontinuous. Continuous work delays the start date of tasks to enable work continuity.

The Location-Based controlling system has four stages of information (Seppänen, 2009): baseline; current; progress; forecast. The baseline schedule is the feasible owner – approved schedule, used to make commitments to subcontractors. The current schedule of the project is formed by detailed tasks. Each baseline task is linked at least to one detail task. The detail planning may include adding more detail to locations or adding more detail task, or changing data according to subcontractors agreement. The progress stage monitors actual performance of the project by recording task times in each locations. The forecast stage uses the current plan and progress information to calculate a schedule forecast. Control charts shows the schedule status of each task and location. The schedule forecast is compared with the planned logic to evaluate the impact of project variances in the workflow. Production managers can use this information to make decisions, and specific alert signals termed alarms are created to highlight future interference between trades and to allow timely reaction of the management. Alarms are early warnings of any upcoming production problems to a successor task caused by a predecessor task (Seppanen, 2009).

Location – based techniques include methods that have been termed in a very different way: line of balance, repetitive scheduling methods, linear scheduling, flow line etc. The leading idea is that networking techniques are not able to effectively control the timing of construction projects. In fact, such techniques can work efficiently in small non-repetitive and simple projects, but on larger and more complex projects the need to take account of resource limitations has severely impaired their effectiveness (Kenley and Seppänen, 2010). Flow line-based techniques take into account two specific components of construction projects, locations and resources, depicting the movement of crews in the construction site. In fact, CPM-based networking techniques for construction scheduling can lead the project scheduler to develop a schedule model that violates the principles of flow process design and improvement in construction projects, leading to non-optimal flows of work and resources, thus increasing non value-adding activities (Koskela, 1992). Although, flowline schedule needs to depict a project logic, and this can be done through a CPM-based network. Therefore, the project schedule model still can be developed with a properly designed and

implemented networking technique, that can still be the basis for a suitable scheduling process of a construction project.

1.1.3 The schedule quality

A sound project schedule can be helpful in managing construction production with the purpose of improving productivity and quality through better planning and control. A good quality project schedule merges cost and technical data to support project management decision and actions, so project managers and stakeholders have to use project scheduling to understand project status and the probable development of future project activities. Therefore, schedule quality, meaning quality of scheduling process and of scheduling output, can be very important in the selection of an appropriate project organization form and of the construction strategy (Russell, Tran, Staub-French 2014). As previously mentioned, productivity improvement in the construction process can be implemented through project scheduling, seen as a method of increasing the efficiency of the production system (Kenley, 2014). In fact, construction efficiency can be tackled through scheduling, as scheduling can manage different problems of construction such as following:

- processes productivity,
- processes coordination and safety,
- connections between system and processes.

A good schedule maximises productivity, finds an optimal balance between risk and duration and it is feasible to implement. A good schedule does more than merely achieve the shortest time for the project (Kenley, Seppänen, 2010). In fact, Griffith (2005) and the guide of the United States Government Accountability Office (GAO) report that there is a significant relationship between good scheduling practices used early in the project life cycle and the ultimate success of the project (GAO, 2009). It is clear that assuring the quality of the scheduling process and of the schedule itself can be a winning strategy for the achievement of project success. A schedule quality survey can also be thought of as a key process of construction project management and an indicator of overall process quality (Zwikaël and Globerson, 2004). However, the goal of project scheduling quality can be achieved with difficulty in construction projects, though the project team has allocated much effort to it.

A quality driven scheduling process is, anyway, difficult to encounter in actual projects. The American Road and Transportation Builders Association – ARTBA (2012) indicates the following aspects of construction schedule and scheduling process to explain the schedule quality.

Schedule quality:

1. Work structuring
 - a. Schedule should be a management tool, not just a required report.
 - b. Schedule should be a tool to allocate manpower and resources as efficiently as possible.
 - c. Planning and scheduling is not an administrative function.
 - d. Time is money and a proper schedule saves time.
 - e. Baseline should reflect how the contractor envisioned the project at the time of the bid.

2. validity of data:
 - a. Baseline schedule should be based on contract documents and specifications;
 - b. Validity of data. Schedule should be an unbiased representation of the facts regarding the project.
3. Level of detail, WBS:
 - a. the complexity of the schedule should vary based on project complexity. The owner should define the required level of detail.
 - b. Baseline schedule should be grouped and sorted by an appropriate means, i.e. Work Breakdown Structure, Activity codes.
4. Total project duration / Contract time. The owner should establish the initial contract time taking into account:
 - a. all construction phases,
 - b. utility installations and sequencing,
 - c. weather allowances. Schedule should incorporate any anticipated inclement weather days and / or seasonal restriction.
5. Format. Schedule submissions should be in an electronic format and hardcopy.

Scheduling quality

6. Baseline and Schedule updates:
 - a. baseline should not change, changes are to be incorporated in subsequent updates;
 - b. schedule updates and revisions should show accurate progress through the data date and be submitted respecting due dates. Logic should be revised in the appropriate update.
 - c. The contractor should provide a written schedule narrative with every schedule update. The narrative should address problem areas, delays, logic revisions, critical path.
 - d. Update frequency should be reasonable.
 - e. Accurate "as-built" dates for all completed work should be recorded.
7. Floats and Delays.
 - a. Schedule should be used to mitigate any changes and delays.
 - b. Time extensions should be automatic in case of delays beyond contractor's control, especially if critical path is impacted by more than 50 percent (additional work, severe weather days).
 - c. Unusually severe conditions should be compensated by the owner on a monthly basis.
 - d. Float ownership. Float ownership clause should be included in scheduling specifications.
8. Partnership/cooperation.
 - a. For the schedule to be effective there must be a partnership atmosphere. Both the owner and the contractor should cooperate at the schedule management process. Schedule maintenance rules should be set before project start in an initial partnership meeting.
 - b. The purpose of the schedule for all stakeholders should be the successfully completion of the project.
 - c. Claims for money or time. Schedule is a management tool, not to be used only for claims for time and money.
 - d. All sides win if a project can be achieved with an early completion.
 - e. The feeling that the construction schedule is an important tool starts from the top, from owner to contractors.
9. Construction Scheduling expertise

- a. While the owner might be the scheduling expert, the contractor is the construction expert. Mutual respect among stakeholders is critical to ensure cooperative efforts.
 - b. The owner's schedule reviewer should have some construction experience. Both sides need the expertise to understand the schedule. The contractor's schedule representative should be sufficiently proficient in the use of scheduling software and should have access to an experienced field-knowledgeable mentor (Superintendent, Project Manager)
10. Schedule Cost: the owner should provide an allowance bid item to compensate costs for schedule related activities and updates due to delays beyond the contractor's control.

In summary, according to the ARTBA list of aspects a good quality scheduling can be achieved via few elements: work structuring i.e. process design; WBS and project management processes; contract vs. scheduled total project duration; schedule maintenance; construction and scheduling knowledge.

In academia, the quality of construction schedules has been the objective of research work in a rather limited manner. Obviously, textbooks and scientific papers about construction project planning methods and tools have always addressed schedule quality, i.e. described methods, rules and good practices for successful planning and scheduling. However, the scheduling community has expressed many times the need of schedule development recommended practices for quality assurance of the scheduling processes and of scheduling deliverables in the construction sector (Moosavi and Mosehli, 2014). Therefore, some industrial standards exist which cover procedures to achieve schedule quality, but most of those standards are outside the construction context (PMI, 2007; AACE, 2009; DCMA, 2012; APM 2012 GAO, 2012, PMSC, 2012). Moreover, they aim at the evaluation of quality with a monitoring and control orientation, meaning they are not built directly to drive the scheduling process.

The research gap to be filled is to understand schedule quality in the construction environment and to propose a process – oriented schedule quality system that can also be used as a driver of the scheduling process toward quality.

1.2 Research Design

1.2.1 Research objectives

This dissertation aim is to contribute to the body of knowledge of project planning, scheduling and controlling, particularly focusing on schedule management and project control of construction projects. The research work recognises the importance of scheduling methods for project time management and identifies quality characteristics of schedules and of scheduling process as well as proposing a quality-driven approach for project scheduling.

The quality of a construction schedule and of scheduling process is the main object of this study, with the aim of proposing guidelines and a specific approach for the delivery of good quality schedule for construction projects. Time - driven scheduling or cost - driven scheduling are ordinary routine, while quality driven scheduling can be seldom found in actual construction projects. What is needed is a quality - driven scheduling that is a proven and reliable scheduling process enabling timely delivery of a schedule that meets its different quality criteria. A construction schedule presents linked activities with planned dates, durations, milestones and resources (PMI, 2013) that is the timetable for a Project (APM, 2006) and that describes the

production process that will be performed (or is in progress). Therefore a quality schedule can contribute to the implementation of reliable construction processes, and to the goal of delivering end products that meet all project objectives.

Starting from this viewpoint, the dissertation aims at understanding the quality of a construction schedule and the contribution of scheduling to construction process organization and to the project control phase, therefore increasing project quality. Firstly, schedule quality is understood as the fulfilment of a set of specific requirements originating from the nature of schedules and scheduling process. Therefore, it is possible to adequately develop a sound and good quality schedule model by fulfilling these requirements. Secondly, the dissertation proposes the improvement of project control functions by the implementation of a Quality Breakdown Structure. Thirdly, the use of resource-space charts for network plotting is the proposed method to create a quality and process-oriented construction schedule, thus completing the planning, scheduling and controlling system of project management.

The main goal of the dissertation is the understanding of construction schedule quality. This goal can be achieved through the analysis and detection of the following topics:

- schedule quality of construction projects;
- construction quality in project control processes; and
- quality driven scheduling method.

These topics are investigated thoroughly in the appended papers and summarized in this dissertation.

1.2.2 Research questions

This dissertation pursues the understanding of quality in construction scheduling, meaning the degree to which a scheduling process and a schedule fulfil the requested requirements, meaning also the integration of quality in project control processes, and the adherence of used scheduling method with construction processes. Therefore, three different topics are objectives of this study: a) schedule quality of construction projects; b) construction quality in project control processes; and c) a quality driven scheduling method. These three research paths originates from the following three research questions.

The first research question is about quality of project schedules and of scheduling. The study of existing literature has revealed that the current approaches to schedule quality lack of contextualization in the construction sector or suffer from a contract management approach that highlights monitoring and control processes neglecting in some way the scheduling process behind. As quality is the degree of fulfilment of requested requirements by processes and deliverables, this research question focuses on the requirements needed for the scheduling function of construction projects. The main idea is that it is possible to detect and create specific requirements for this function that can allow project stakeholders to assess the quality level of the schedule and to drive a quality scheduling process in construction.

RQ#1) What is schedule quality?

The second research question broadens the range of analysis to the whole project level. As quality assessment is usually performed at the project level, meaning construction processes and products perceived as a whole, and the corresponding and needed set of requirements are generally well-known and adopted by project stakeholders, there is a need to link quality creation at the project level to project schedules for

project control purposes. Quality control, at the project level, is not integrated with the traditional time-cost project control approach. Planning for quality is seen as giving time to quality-related activities, while the flow of quality production should be delivered and highlighted through the scheduling process. Therefore, the second research question is:

RQ#2) What is scheduling producing in terms of quality?

The third research question recognizes that construction projects need a specific approach for project scheduling. This is because construction projects are special projects, and have specific characteristics that need specific project management methods and approaches (PMI, 2007). The network-based approach is criticised, and the proposed solutions aim at creating a flowline-based scheduling model. Though activity networks are the most used approach for project scheduling, as they represent conversion activities and their dependencies very well (Koskela, 1992), and flowlines display process flows, a quality driven approach for construction scheduling should be composed of both (Kenley, Seppänen, 2010), without neglecting the networking approach for project modelling but improving it. As resources and spaces need to be clearly indicated in the scheduling model, a new way of clearly representing schedule model is needed, based upon the activity network schedule model. Therefore, the third research question is:

RQ#3) Can the activity network schedule model be process-oriented and quality driven?

In figure 1.2 research questions and aim are exemplified.

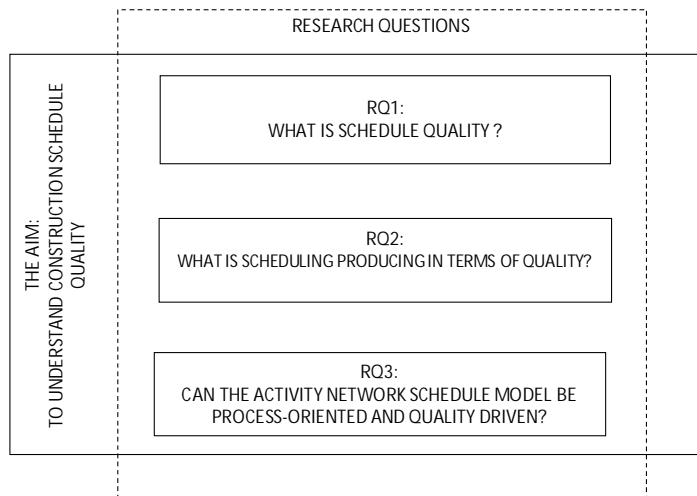


Figure 1.2: Research questions and aim

1.3 Research methodology

1.3.1 Research context

The research itself belongs to a mainstream research context, which aims at identifying the most suitable approach to construction project planning, scheduling and control. Of foremost importance is the recent work of Olli Seppänen and Russell Kenley termed Location – Based Management System (LBMS) (Seppänen, 2009; Kenley, Seppänen, 2010). The LBMS is conceived as an entirely new production system for construction management using flowline scheduling and a CPM – based layered logic between tasks and activities. LBMS is a comprehensive management system - from design, through measurement, scheduling, and visualization and control – which emphasises cost reduction and quality improvement. The authors argue that the scheduling approach has to be based upon the movement of resources – crews – through the different locations to the construction site. The chosen approaches for the scheduling model are flowlines representing activities performed in the different space units of the building/construction by crews, that are linked to each other with a layered logic i.e. networking relationships. Location-Based Management system is based upon the following principles: Location Breakdown Structure, location-based quantities, CPM-based layered logic and algorithm, workflow optimisation. Basically, the core of the LBMS is the Location-Based Planning with flowline.

The flowline approach has old roots in construction management research and practice, as described in the following theoretical foundation chapter. Another essential milestone in this research line is the work of Alan D. Russell. Since 1993, Russell (Russell and Wong, 1993) developed a construction management approach termed Representing Construction (REPCON) based upon an integrated scheduling system which coordinates a network logic, including generalized Precedence Diagramming logic links between activities (Finish to Start, Start to Start, Finish to Finish and Start to Finish), with linear planning or time – space charts. REPCON introduces different planning structures, i.e. activity types, which allow one to model time and space simultaneously. A planning structure is specified to reflect the work locations where instances of the activity occur, the order of operations and various data about construction crew, work continuity constraints and interruptions, and resource assignments (Russell, Udaipurwala, Wong, 2003).

Schedule modeling and flowline approach for building construction projects was also the research focus of Kähkönen (1994) who developed a semi-automated method for schedule generation. The study addressed activities' dependencies in scheduling, and working areas and resources were seen as major players of schedule logic. A construction project model consists of project-dependent and project-independent parts. The project dependent part consists of data for a particular project that the planner must define, particularly locations of the project and their sequence of construction, as well as activities needed to build each location and available resources. Then, a specific knowledge – based procedure creates the project – independent part of the schedule model. The model has been successfully implemented and tested in the form of a computer program.

1.3.2 The research method

Qualitative research is a broad methodological approach that encompasses many research methods, in opposition with quantitative research that deals with quantification in science. Qualitative research has

the aim of understanding some specific objects of study, while quantitative methods aim to measure the studied phenomenon (Guba, Lincoln, 1994). What knowledge is, and the ways of discovering it, are subjective (Scotland, 2012). Therefore, a research paradigm to drive the research work behind this dissertation is needed. A paradigm may be viewed as a set of basic beliefs that deals with ultimate or first principles and represents a worldview. A paradigm consists of three components: ontology, epistemology and methodology (Guba, Lincoln, 1994). Ontology is the study of being, meaning that ontological assumptions are concerned with what constitutes reality. Epistemology is concerned with the nature and forms of knowledge. Epistemological assumptions are concerned with how knowledge can be created, and the nature of the relationship between the knower or would be knower and what can be known. Methodology is the strategy or plan of action which lies behind the choice of particular methods. Methods are the specific techniques and procedures used to collect and analyse data. Therefore, all research methods are committed to an ontological and epistemological position (Scotland, 2012). The definition and relation of ontology, epistemology and methodology define the four main philosophical positions in qualitative research: positivism, postpositivism, critical theory and constructivism (Guba, Lincoln, 1994; Eriksson, Kovalainen 2008).

The ex-ante perspective of the research work behind this dissertation is a combination of qualitative and quantitative (mixed) research dealing with the constructivism paradigm. The ontological position of constructivism, or the interpretative paradigm, is relativism, meaning that reality can be understood in the form of multiple mental constructions experientially based. Constructions are not more or less true in any absolute sense, but simply more or less informed and/or sophisticated. The epistemological perspective is based on real world phenomena, and the investigator and the object of investigation are assumed to be interactively linked so that findings are created as the investigation proceeds. The methodology is inductive. (Guba, Lincoln, 1994; Scotland, 2012). Research evaluation entails: a) reliability and / or dependability, meaning that the research process and findings can be replicated; b) internal validity and / or credibility, meaning the providing of evidences and credible and justifiable accounts; c) external validity and / or transferability, meaning that it can be used by someone else in another similar situation (Eriksson, Kovalainen, 2008; Scotland, 2012).

The research design has employed a mixed research methodology. Firstly, the construction scheduling context in the project management approach was detected, and three research questions were identified. The three research questions were used as starting points for the development of three different work packages encompassing the main research work. Secondly, a widespread literature search was performed and a theoretical foundation of the problem of schedule quality in construction projects and its outputs on project control was built. The process of scheduling in the project control context was observed in depth, and constructive solution ideas were proposed for each work package of the research and implemented in case studies. Data from the research were generated analysing actual case studies and sample projects, i.e. typical building sub-processes deduced from actual case studies. The constructive research approach implies that the successful implementation of the solution concepts in the case studies makes it credible that the solutions will also work in similar cases of actual construction projects. Because the necessary condition for the credibility of the proposed concepts and methods is the real-world implementation and functioning of the proposed solution concepts, real-world case studies have been implemented in this dissertation (Lukka and Kasanen, 1995).

The understanding and definition of schedule quality for a construction project, meaning quality of scheduling process and products, is a challenging task, and a few researchers and practitioners, owners or contractor's agencies have proposed solutions and approaches to tackle the problem. The seminal work of De La Garza (1990) and the consequent research works and standardization efforts indicated the way forward for the construction schedule quality assessment. Starting from this viewpoint, this dissertation aims to develop a simple to implement, but complete, method for construction schedule quality assessment and its full understanding through implementation of a quality driven scheduling approach, based upon resource-

space charts for network diagramming, and proposing the use of Quality Breakdown Structure (QBS) in project control processes.

There are three proposed solution ideas. The first is a procedure to guide and control the scheduling process of the owner's consultant or of a project planner of a Small – Medium sized Construction Enterprise. The constructed procedure was termed Schedule Health Assessment and can be performed with a simple set of score sheets to record the quality analysis performed. The quality level achieved by construction schedule is synthesized through five Key Performance Indicators (KPIs), termed Schedule Health Indicators. Thus, the research is believed to produce an innovative “construction” meant to solve the initial real-world problem (Lukka, 2015). The developed method can offer a conceptual framework of the scheduling problem in general. The use of a Quality Breakdown Structure for project control is the proposed concept solution for capturing project level quality creation. Then, the REPNET proposed method that entails resource – space charts for network diagramming, has been implemented as a quality driven detailed scheduling approach for a construction project. The case studies presented in the papers offer the possibility of proof of concept and generalized conclusions (Lukka, Kasanen, 1995), because of the possibility of discussing specific results and the subject area of construction scheduling in general.

The research work of this dissertation can be classified, ex-post, at first as a qualitative research methodology and constructive approach (Kasanen, Lukka and Siitonen, 1993; Lukka and Kasanen, 1995, Lukka, 2000). After relevant problem detection, i.e. the inadequacy of real – life schedules for construction projects, a through review of existing tools and methods for quality driven scheduling has been performed, and constructive solutions were proposed. However, the modelling and “construction” of the proposed solutions required computing and scheduling, thus involving also a quantitative research methodology. Therefore, a mixed research approach was adopted in this dissertation (Amaratunga, Baldry, Sashar, Newton, 2002).

1.3.3 Research methods and approaches of the appended papers

The research methods and approaches were selected based on the nature of the research questions faced in each paper. A qualitative research method was selected particularly in the first paper, that mostly analyses the state of the art and the research practice of the selected concepts (paper I), while a mixed research method and the constructive approach was implemented in the other papers which involve the building of a model and the evaluation of the outputs (paperII, III, IV, V, VI, VII and VIII). The papers present the required research effort for portraying the basis of good quality scheduling and schedules, possible solutions for quality driven scheduling and their testing.

Paper I is a literature review of construction control methods, which have been classified as project oriented (traditional methods), or process oriented (innovative methods). A qualitative research method is followed. The paper addresses the Project Control theme aiming at understanding different methods, tools, control data and KPIs for construction management. The paper focuses on construction data and KPIs that can be delivered by traditional time and time / cost control methods (i.e. Earned Value Method) and by innovative methods as the Last Planner System, the Theory of Constraints, the Location – Based Management System.

In paper II the relevant problem of the measurement of the quality performance of a construction project was individuated, meaning how the quality of a construction project is delivered and controlled. A deep understanding of the project control problem in construction was obtained by literature analysis,

focusing on available KPIs to implement quality related metrics. The quality delivered is both the technical quality of the final product (the building or the civil engineering infrastructure) and building process quality. The solution idea proposed was the adoption of a Quality Breakdown Structure as a basic tool to consider the various elements of construction quality like process quality and product quality. The solution idea was tested in two case studies of building construction, and one of them was presented in the paper. The mixed research method and the constructive approach are followed.

Paper III individuates the problem of the development of an adequate construction schedule. Then a deep understanding of the project time management problem in construction was obtained by literature analysis, focusing on scheduling methods and their effects on the scheduled project. The solution idea proposed was the resource flow optimization achieved by a heuristics algorithm for resource scheduling and by plotting the Precedence Diagramming network on a resource-space chart. A sample project was used to test the constructed method, termed REPNET. The mixed research method and the constructive approach are followed.

Paper IV individuates the problem of defining the quality of a construction project schedule. A deep understanding of the schedule quality problem in construction was obtained by literature analysis, focusing on the needed quality requirements. The solution idea proposed was a procedure to guide and control the quality of a construction schedule in the design and maintenance phase, based upon the selection of quality requirements. The method was tested on a case study and termed Schedule Health Assessment. The mixed research method and the constructive approach are followed.

Paper V is a proof of concept and feed-back of the proposed “constructed” method for the schedule quality assessment. The paper is a connecting paper that aims at focusing the developed schedule quality assessment method (in paper IV) on the construction process safety problem. The aim is to validate the proposed Schedule Health Assessment method with the “3S” rule for construction scheduling meaning “Safety, Space and Structure”. The paper highlights the need of flow-line view of the construction schedule to be really process-oriented. The mixed research method and the constructive approach are followed.

Paper VI develops the REPNET method with the addition of a Location Breakdown Structure (LBS) in the resource-space chart. The LBS allows loading a maximum number of resources (crew) in each space unit, thus defining the available space capacity of working crews. In this way project scheduler can verify the quality of the produced schedule during the planning and scheduling process, as dimensions of workspaces and their congestion limits, safety spaces and protection spaces can be easily verified. The method has been tested on a sample project, and a control chart can be plotted for each week to facilitate the monitoring of the project status. The mixed research method and the constructive approach are followed.

Paper VII is a proof of concept and feed-back of the REPNET through implementation in a rehabilitation construction project. The use of a process based paradigm for planning and scheduling can help companies’ construction managers to create different production scenarios to choose the more suitable strategy for a building construction project, delivering a good quality schedule. The mixed research method and the constructive approach are followed.

Paper VIII develops a deeper Schedule Health Assessment method via literature study of the methodical grounds for assessing schedule quality. These findings combined with the experiences from practical implementations have resulted in the definition of a metric to measure schedule quality of construction projects. A case study was investigated in cooperation with the company’s project scheduler. The mixed research method and the constructive approach are followed. The research papers, research methods, research approaches and data are summarised in table 1.1.

Table 1.1 Research papers, research methods, research approaches and main data sources used in the papers

Paper	Research method / approach		Main data sources
	1.	2.	
Paper I	Qualitative	Literature review	Pertinent literature
Paper II	Mixed/Constructive	Case study	Building construction projects (A and B)
Paper III	Mixed/Constructive	Sample project	Example building sub-process
Paper IV	Mixed/Constructive	Case Study	Building construction project (C)
Paper V	Mixed/Constructive	Case Study	Example building sub-process
Paper VI	Mixed/Constructive	Case Study	Example building sub-process
Paper VII	Mixed/Constructive	Case Study	Building construction project (D)
Paper VIII	Mixed/Constructive	Case Study	Building construction project (E)

All the appended papers have been accepted, presented and published in relation to international research conferences, or published in international scientific journals:

- Paper I and VII have been presented by the author in the ISTE A 2013 and 2016 International Conferences (ISTEA is the Italian Association of Academics Researchers of Building Production, proceedings are published in English);
- Paper III has been presented in the Construction Management Workshop organized in 2013 in the Ravenna branch of the School of Engineering and Architecture of the University of Bologna.
- Paper IV in the ICEC IX World Congress held in Milan in 2014.
- Paper V in the 8th Nordic Conference on Construction Economics and Organisation in Tampere in 2015.
- Paper VI in the CIB World Building Congress held in Tampere in 2016.
- Paper II was published in 2013 in the Journal of Frontiers in Construction Engineering as an evolution of the research line of construction quality in project control.
- Paper VIII is the final achievement of the research path in 2016, the journal of Construction Management and Economics.

1.4. Research structure

The research work is composed by the three Work Packages (WP) corresponding to the three research questions. The WPs are interdependent and indicate the following research structure (figure no.1.3):

- Work Pack # 1 Construction schedule quality
- Work Pack # 2 Construction quality in project control
- Work Pack # 3 Construction scheduling proposed method

The aim is to understand schedule quality. Each WP of the research has been developed by the production of papers. Eight papers and their contents are part of the research structure and content. Each paper mainly relates to a WP and a research question. The structure of the research is presented in figure n.1.2, which illustrates how the research aim, questions, Work Packages and papers are all linked together. The objectives of the research work can be achieved through the development of three work packages (WP).

1.4.1. Work Pack #1 Construction schedule quality

Research Question:

- What is schedule quality?

WP Design

The study will start with a literature review and analysis of the state of the art and understanding of schedule quality. As quality can be understood as the fulfilment of needs by the requested performances of a product, the study of the schedule quality requirements constitutes the core of the WP. A constructive approach will be used to develop a schedule quality model and a method to check schedule quality, which simultaneously can guide project schedulers in construction schedule development.

WP Expected Results

The objective of the WP is to develop a method of understanding and measuring Project Schedule Quality in Construction. Quality of a construction schedule can be defined as the satisfaction of a set of requirements according to specified performance indicators. The developed method is termed "Schedule Health Assessment". The Schedule Health Assessment process quantifies schedule performance, thus enabling a project team to implement a proactive approach to construction scheduling. The "3S" rule for construction scheduling, meaning "Safety, Space and Structure" is used to synthesise quality requirements of the construction process. Therefore, process design through schedule model implementation must satisfy the "3S" rule to obtain a good quality schedule. Safety and structure requirements can be fulfilled through activity sequencing, while space requirements can be fulfilled by a flowline view on a resource – space chart for schedule creation. The method has been tested on actual case studies.

1.4.2. Work Pack # 2 Construction quality in project control

Research question:

- What is scheduling producing in terms of quality?

WP Design

The study will start with a literature review and analysis of the state of the art and understanding of the contribution of project control to the quality of the construction process and of the construction seen as the final product. A constructive approach will be used to understand and measure quality produced in the construction process and the contribution of project control methods.

The measurement of the performance of a construction project is a basic issue of Construction Management, and it is based upon project – related indexes known as Key Performance Indicators (KPIs). Key Performance Indicators are project measurements that substantiate the health of the project and can be used to predict the future performance of the construction project. The measurement of the performance of a construction project is usually based upon different metrics relating to time, cost, resources, quality and project specific indicators. For time, cost and resource usage it is simple to transfer project performance into meaningful indexes relating to work packages or to the entire project, though it is difficult to define and evaluate quality – related issues and metrics for construction project control.

WP Expected Results

The objective of the WP is to develop an approach to understand, integrate and measure quality production in Construction Projects through scheduling. The method is based upon the definition of a “Quality Breakdown Structure” (QBS). The Quality Breakdown Structure quantifies project quality performance, thus enabling the project team to implement a proactive approach to construction quality production through specific quality oriented KPIs. QBS is an innovative method to design and control quality creation in a construction project. The method has been tested on actual case studies. Quality related performance indicators can be loaded to the construction project scheduling model, with the goal of showing to the Project Manager and to Stakeholders the achieved versus the planned quality in the project status.

1.4.3. Work Pack # 3 Construction scheduling proposed method

Research Question:

- Can the activity network schedule model be process-oriented and quality driven?

WP Design

The study will start with a literature review and analysis of the state of the art and understanding of the characteristics of a construction oriented schedule model. A constructive approach will be used to develop a process oriented scheduling approach, based upon resource-space charts for activity network plotting.

Construction production is typically highly dependent upon space to move, store and fabricate materials and building components, and to perform transformation and assembling activities. Construction is also characterised by resource limitations. The goal of construction planning and scheduling is to provide a logical order for activities while taking into account safety, space and logic requirements. Construction process scheduling should also incorporate specific features of work-flows of project activities through work spaces. The Location-Based Management System (LBMS) is a recent and innovative method that aims at planning and managing construction projects in a process-oriented way, taking into account activity locations on-site.

An improved scheduling method for construction operations has been developed based upon a Precedence Diagramming Network plotted on a Resource–Space chart and termed Repetitive Networking Technique (REPNET). Space Units of the project are identified by a Location Breakdown Structure (LBS) like in the LBMS System (Kenley and Seppänen, 2010), and project activities are identified by a two dimensional coordinate system based on resources (i.e. construction crews) and working spaces (e.g. floors of a multi-storey building). As the Precedence Network is plotted on a resource – space chart, space units can be characterized by a maximum resource capacity number for each activity type, thus defining the available space capacity of working crews. In this way, the project scheduler can verify the quality of the produced schedule during the planning/scheduling process as dimensions of workspaces and their congestion limits, safety spaces and protection spaces can be easily verified. REPNET is a location & resource based planning system based upon Precedence Diagramming and flowlines.

The proposed scheduling approach can help inexperienced project schedulers to identify specific resource requirements for spaces needed for activities, and to define locations of these spaces and resources on a building site. In particular, a process-oriented construction schedule can help construction managers to implement different scenarios of project strategy, thus creating a decision support system model for building construction projects. The method has been tested using sample projects and an actual case study.

WP Expected Results

The objective of the WP is to further develop the resource – space chart proposed method for plotting of activity networks. The REPNET is a process-oriented construction scheduling approach that address quality driven project scheduling. Workspace scheduling and project strategy can be easily implemented with the REPNET, and a quality schedule can be easily developed. At this stage of the research work, schedule quality can be defined as the desirable level of understanding of the construction process transferred into the scheduling model.

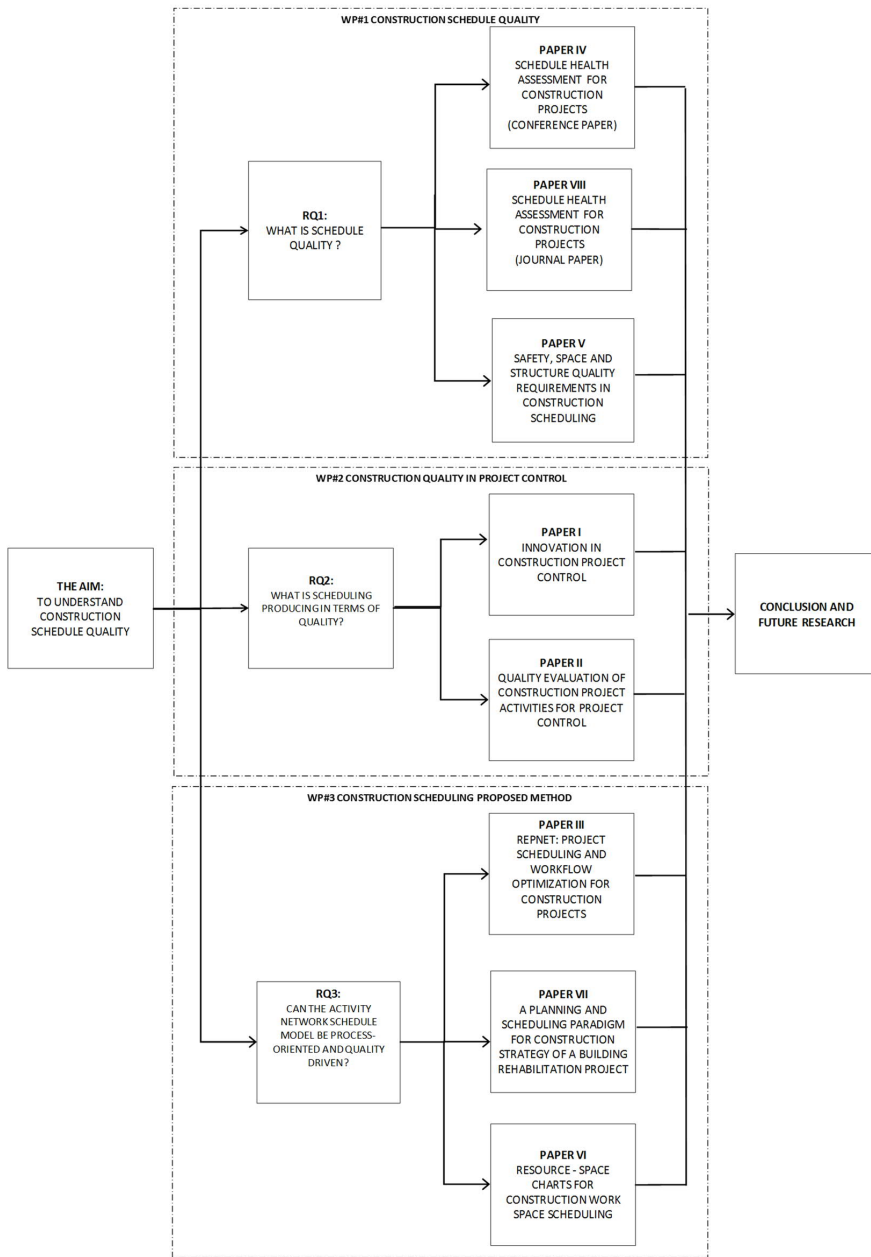


Figure 1.3: Research structure of the dissertation

1.4.4 Research structure: appended papers

The dissertation consists of two appended articles that have been peer reviewed and published in academic journals and of six appended articles that have been peer reviewed and published in scientific conference publications.

Paper I provides a review of ICT – based construction project control methods and discusses their benefits and limits to explain the performance of modern construction controlling processes. The main goal of the project monitoring process is the measure of project performance achieved with metrics such as the Key Performance Indicators (KPIs), which are closely related to project models beyond project control techniques.

Paper II investigates the way forward toward implementing quality related Key Performance Indicators (KPIs) for construction project control. The Quality Breakdown Structure (QBS) is adopted as a basic tool to consider the various components of construction quality. The purpose of Paper II is to investigate how Project Managers can measure construction quality in each task or component of the project, and if construction quality of the whole project can be summarized into a total value that is achieved when a milestone is reached. The method has been tested on actual case studies.

Paper III describes an improved method for resource and space-based construction scheduling, termed Repetitive Networking Techniques (REPNET). REPNET is based on a Precedence Diagramming network plotted on a resource-space chart and presented with a flow-line chart. The developed heuristics of REPNET are used to carry out resource timing while optimizing process flows and resource usage. The method has been tested on a sample project.

Paper IV has the aim of assessing the quality of a schedule of a construction project and the characteristics that a good quality schedule should have. This can be defined as “Schedule Health Assessment”. A set of quality requirements from previous literature has been selected to define a metric to measure schedule quality. The schedule requirements have been classified and weighted related to their importance, and a method of schedule health assessment has been developed. The method can help project planners to produce a good quality schedule from the outset of the project and, during the execution phase, it can be used to perform a schedule health assessment to detect deficiencies and issues to be addressed for construction control purposes. The method has been tested on an actual case study.

Paper V has the aim of implementing the “3S” rule for construction scheduling in the proposed Schedule Health Assessment method. The three S’s are Safety, Space and Structure, meaning that the planned process should provide a safe working environment to construction workers, sufficient space to perform construction activities and the required sequence of construction operations and project phases. The aim of the study is to implement a schedule quality assessment method that takes into account the “3S” rule of construction process. The requirements according to “3S” can be successfully integrated in a Schedule Health Assessment method, but a flow-line chart is needed to facilitate their implementation and control, thus the chart becomes a new requirement for construction schedule quality control. The method has been tested on a sample project.

Paper VI has the aim of testing the REPNET method for workspace scheduling, taking into account safety, space and logic requirements on a sample project. Space units of the project are identified by a Location Breakdown Structure (LBS) like in the LBM System, and project activities are identified by a two dimensional coordinate system based on resources (i.e. construction crews) and working spaces (e.g. floors of a multi-storey building). As the Precedence Network is plotted on a resource – space chart, Space Units can be characterized by a maximum resource capacity number for each activity type, thus defining the

available space capacity of working crews. In this way the project scheduler can verify the quality of the produced schedule during the planning and scheduling process, as dimensions of workspaces and their congestion limits, safety spaces and protection spaces can be easily verified. The development of weekly control charts can ease the monitoring and controlling process, pointing out completed and in progress activities with their successor spaces. The method has been tested on a sample project.

Paper VII investigates the use of the REPNET method to create different production scenarios to choose the more suitable strategy for a building construction project. Strategic decisions for a construction project play a fundamental role in the search for project success, and this is more evident in rehabilitation construction projects due to site constraints. A case study of an actual building rehabilitation project has been used to compare the project schedule prepared by the owner for the bid phase and the different scenarios created by the company for the construction phase. The proposed planning and scheduling paradigm can be used to optimize the construction strategy, especially in building rehabilitation projects where multiple choices for activity sequencing are possible.

Paper VIII suggests and evaluates the proposed Schedule Health Assessment approach. Methodical grounds for assessing schedule quality have been studied via literature analysis of the development of appropriate solutions to assess the quality of construction schedules. These findings combined with the experiences from practical implementations have resulted in the definition of a metric to measure schedule quality for construction projects. It includes seventy-five scheduling requirements classified into five groups: general requirements, construction process, schedule mechanics, cost and resources and control process. This structure forms a core for the developed method to assess construction schedule quality termed as the Schedule Health Assessment. The developed method also has the purpose of assisting project planners in producing and maintaining good quality schedules starting from the outset of a project until its completion by using the method to detect deficiencies of project schedules and other critical issues having importance with respect to schedule maintenance. The method has been tested on an actual case study.

The dissertation's summary integrates the findings of the papers.

2. Theoretical foundation

2.1 Introduction: project planning, scheduling and control systems for construction

Traditional project planning, scheduling and control systems focus principally on project factors, time, cost and quality, because the main objective of Project Management is project delivery within time, budget and quality constraints. Therefore, the managing of projects is mostly concerned with the three knowledge areas of Time Management, Cost Management, and Quality Management (overlooking for a while the other areas, particularly scope management). Time management entails schedule development, management and control, while cost management involves direct and indirect cost control (PMI, 2013), and quality management entails quality assurance procedures. However, time management involves work progress control (PMI, 2013). Really, the estimate of the activity durations and the activity sequence in a construction project is a variable that it is directly linked to resource availability and usage, and thus determines activities' performance in terms of time consumption, direct cost of activities, quality, and safety as a consequence of duration definition and time co-ordination of activities.

2.1.1 Project planning and scheduling in construction

Planning is one of the key functions of the management process, and the project manager's prime activity (Ahuja, Dozzi and Abourizk, 1994). The planning entails the selection of objectives and then the definition of a program or programs with the required procedures for achieving the objectives. Particularly, it comprises evaluation of alternatives and related decision making for future activities. A proactive management style sets a plan and makes it happen, while a reactive management style, or crisis management, results from lack of planning (Ahuja, Dozzi and Abourizk, 1994). A plan is to choose a set of activities and create a logical sequence, while scheduling means also computing activity durations, calculating the total project duration and giving dates to the start and finish of activities. ISO 21500 standard, "Guidance on Project Management," indicates that the purpose of planning is to document the following information in project plans:

- why the project is being undertaken;
- what will be provided and by whom;
- how it will be provided;
- what it will cost;
- how the project will be implemented, controlled and closed.

Planning results in setting time objectives and milestones, and clearly establishes the work to be done to achieve contract scope and cost objectives. Project scheduling is the process used to determine the overall project duration and when activities and events are planned to happen, with the output being the production of a construction schedule. This includes identification of activities and their logical dependencies, estimation of activity durations, and taking into account requirements and availability of resources (APM, 2006). The construction schedule presents linked activities with planned dates, durations, milestones and resources, derived from a schedule model. The PMI defines the schedule model as the representation of the plan for

executing the project's activities used to produce a project schedule along with other scheduling artefacts and planning information (PMI, 2013). The purpose of a schedule is to calculate the start and the end times of the project activities and to establish the overall project schedule baseline. The schedule baseline is the approved version of a schedule model that is used as a basis for comparison to actual project results. A schedule is established at the activity level, and the level of detail of activities defines the "granularity" of the schedule (APM, 2006). A high level schedule is often termed a master schedule, which highlights milestones, while a low level schedule, a detailed schedule, should be process-oriented as the estimated duration of activity is the function of the estimated productivity of resources, of their quantity and of the quantity of product to be produced. Activities in the schedule may be closely related to the Work Breakdown Structure or to contract data and documents. As WBS is a hierarchical structure, different levels of WBS can be used for the creation of master or detailed schedules. In the construction industry, the development and maintenance of the project schedule is the responsibility of a full-time scheduler or a team of schedulers, depending on the size of the project. Scheduling continues throughout the project life cycle, and the schedule management plan establishes the criteria and the activities for developing, monitoring and controlling the schedule (APM, 2006).

2.1.2 Control systems for construction

Project performance must be measured regularly to identify variances from the plan (PMI, 2013). Project Management Institute defines Project Control as the process of comparing actual project performance with planned performance, analysing variances, evaluating possible alternatives and taking appropriate corrective action as needed. A variance is a quantifiable deviation, departure or divergence away from a known baseline or expected value. Project control is basically performed in two phases, the monitoring phase and the controlling phase. The monitoring phase incorporates the tasks of capturing, analysing and reporting project performance compared to a plan. The monitoring action is taken to assess project status or progress. It is clear that monitoring is meaningful if it can be compared with that which was expected. Project status, in fact, can be defined as the set of variances from the plan in the areas of cost, time, scope and quality. While monitoring is to picture what is happening on a project, the control phase involves the determination of actions in response to monitoring results, i.e. changes made to bring expected future performance of the project into line with plan (PMI, 2013). While this theory divides the process of managing a project into two parts, planning and controlling, and there is a value in this viewpoint of project management, it is recognized that it introduces a false dichotomy (Devaux, 1999). In fact, the planning process does not stop during the execution phase of the project, actually the controlling phase is about planning, re-planning really, until project objectives are finally reached. It is a dual system designed and implemented to reduce project risk (Forsberg et al., 2000). It is project management actually. This is the thermostat model (or cybernetic model) of management control or the feedback control model as defined in modern control theory. The core process of controlling is divided into two subprocesses: performance reporting and overall change control. Reporting prescribes corrections for the executing process, and control prescribes changes for the planning process (Koskela, Howell, 2002). This control process has a strong affinity with the well-known quality-oriented production process individuated by Edward Deming (1982) in the Plan-Do-Check-Act (PDCA) cycle. The PDCA cycle can be applied to all processes and to project management processes in particular. The ISO 9000:2015 standard describes the PDCA cycle as follows (figure 2.1):

- plan: establishes the objectives of the system and its processes, and the resources needed to deliver results in accordance with customers' requirements and the organization's policies, and identifies and addresses risks and opportunities;
- do: implements what was planned;
- check: monitors and measures processes and the resulting products and services against policies, objectives, requirements and planned activities, and reports the results;
- act: takes actions to improve performance, as necessary.

The basic factors to be controlled or, better, managed in a construction project are the following:

- baseline project plan;
- budget and cost;
- quality of production, material and product performances, working standards;
- safety of personnel and environmental impact;
- resource usage, personnel conduct and production equipment and plants.

All of these basic project factors are to be managed during project execution. Additional factors to be managed in construction projects are:

- changes in design and project specifications;
- uncertainty and risk on the project;
- project information flow.

The controlling processes, from the planning, monitoring, controlling and re-planning perspective, constitute the core of project management processes (Koskela and Howell, 2002).

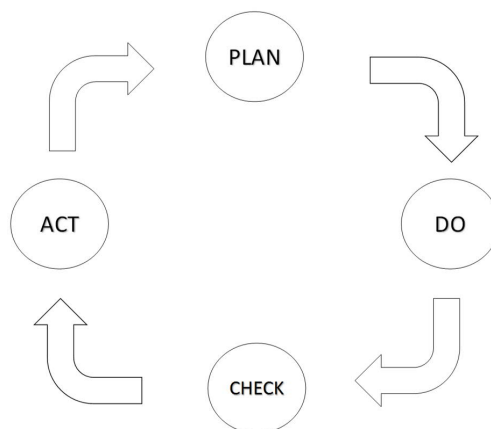


Figure 2.1: The Deming Cycle (Deming, 1982)

In addition to the thermostat model, there is another theory of control that addresses learning and improvement, the scientific experimentation model that focus on finding causes of deviations and acting on those causes (Koskela and Howell, 2002). Ballard (2000) uses this approach in his Last Planner System. Control

consists of measuring the realization rate of work assignment with the Percent Plan Complete (PPC) metric, of investigation of the causes for non – realisation and elimination of those causes.

Kankainen and Seppänen (2003), in the context of the Location-Based Management System, implement a lean controlling process that does not update the master schedule if deviations occur. The reasons for deviation are documented and a control action is planned to minimize the effects on other space-critical tasks. Typically re-planning in construction results in shortening the durations of later activities and the forecast is updated correspondingly. Location-Based controlling system are very effective because they allow a visual comparison of progress compared to the plan (Seppänen, 2009). The Location-Based control system uses locations to generate timely responses through visualization of any problem before they happen. Forecasts are used to remind to production managers the unsolved problems and help take informed control actions. The Location-Based planning model provides more information than a network model, including:

- flow of resources;
- location-based quantities;
- production logic based on locations;
- location-based model that recognises that information from locations are a form of learning.

The LBMS recognises four stages of information: baseline, current, progress and forecast. The Baseline stage is the initial approved location-based plan. The Current stage is the updated version of the baseline that takes into account any new information that was not available in the baseline stage concerning current quantities and new detailed tasks. The Progress stage monitors the actual performance of the project, and therefore update progress status in detailed tasks. The Forecast Stage uses the current plan and progress information to produce a schedule forecast (Seppänen, 2009; Kenley and Seppänen, 2010). Location-based Control system has a strong affinity with the Last Planner system and its can/should/will pull system of production control (Seppänen, Ballard & Pesonen 2010).

2.1.3 Construction scheduling & process modelling

As long as there have been construction projects, the processes of planning, scheduling and controlling have been implemented, starting from simple notes, through bar charts, flow-lines and computerised network – based methods for project analysis and scheduling (Kenley, Seppänen, 2010). Scheduling is an important tool for every manufacturing and engineering process, and, in particular, for construction, as scheduling can have a major impact on productivity and on efficiency of a construction process. In the industrial sector, the general aim of scheduling is to minimize the production time and costs, while assuring the customer of the required quality level. Scheduling tells the construction industry when to build, with which resources, with which equipment and in which chosen activity sequence. Construction scheduling, basically, aims at maximizing the efficiency of the operations and reducing costs without compromising the safety conditions of workers (Frein, 1980).

Surely, it is the combination of planning, scheduling, execution and control that can have a major impact on productivity. The impact of pre-planning on productivity can be tremendous in terms of cost savings and productivity improvement, and in the pre-planning phase and essential element is scheduling and project control (Oglesby, Parker, Howell, 1989; Peurifoy, Ledbetter, Schexnayder, 1996). Better management practices including pre-project planning, team building, Building Information Modeling and safety have been demonstrated to increase productivity (Shan, Goodrum, Zhai, Haas and Caldas, 2011). Kenley and Seppänen (2010) claim that Location-Based Planning has the aim of planning for work to protect

production efficiency as work moves through locations. The goal of Location-Based Planning is to plan for productivity, as it allows to optimise work flow and continuity, therefore protecting and optimising the construction processes.

Innovative construction scheduling tools greatly outperform older scheduling methods, providing the project planner with powerful graphical interfaces, which can be used to visualize the scheduling model of the construction process and the results of the optimization action taken to improve the efficiency of the process itself (Frein, 1980). Often the project view of the scheduling model allows production schedulers to better understand the production process and to recognize new scheduling opportunities which might not be apparent without this insight into the productive data. As an example, with a Gantt chart (figure 2.2) it can be simple to understand which are the overlapping activities of a construction phase, and so the design of construction operations can aim at safety of workers preventing them from interference-related hazards. Process logic is really made clear with an activity network such as Activity On Node (AON) Precedence Diagramming, which shows the relationships between activities or between sub-processes, i.e. the sequence of activities due to technology requirements and resources' flow. In addition, critical activities and critical paths are detected, thus giving project managers a strategic insight into construction project time performances and requirements (figure 2.3). Finally, with a flow-line based scheduling method (figures 2.4), the movement of resources through the building site can be easily visualised, and it will be simple to track the workflow and to detect inefficiencies in the construction processes due to lack of resource organisation. Actually, project scheduling creates a building production model which aims to improve and assure the planned performances of the project.

Since project scheduling can be considered as one of the basic methods of construction project management, it can be understood why previous literature confirms that the success of a project depends in part on having a good quality and reliable schedule that defines when each activity will occur and with which duration, and how each activity is related to the others (U.S. GAO, 2012). The project schedule provides not only a road map for systematic process implementation, but also the means to measure progress, identify and resolve potential problems and promote accountability at all levels of the project. The schedule provides a time sequence for the execution of the project's activities related to their duration and helps stakeholders to understand both the dates for major milestones and for critical activities that drive the process. Project schedule is also a vehicle for developing a time-phased budget baseline, and it is an essential basis for managing trade-offs between cost, schedule, scope or quality. Scheduling allows Project Management to decide between possible alternatives of activity sequence, and determines flexibility of the construction process to optimize resource usage, to forecast the consequences of management decisions, actions or inactions, on events, and to allocate contingency plans to mitigate risks. The effects of variances and changes of project concepts, of detailed design and of building processes can be predicted with the schedule, and also the effects of delayed, deleted and added effort. Possible future scenarios for time and cost recovery can be displayed, chosen and tracked (U.S. GAO, 2012).

A process is a series of actions taken in order to achieve a particular end (Oxford dictionary, 2017). Construction scheduling is based upon a production model that synthesizes and explains the construction processes needed to produce the requested construction facility, building or civil infrastructure. Construction process modelling can be achieved in many ways. Traditional construction models are CPM – based networking techniques like Precedence Diagramming Method (PDM) (Fondhal, 1961; Harris, 1978, Moder, Phillips, Davis, 1983). Activity networks are a well-established and efficient way of construction modelling since they show a topological model of the project (figure 2.3), built by a set of activities linked with each other through a set of relationships (Kenley, Seppänen, 2010). The Activity On Node (AON) representation of activity networks can display project logic in a simple and clear way. In general, a construction project consists of a group of tasks performed in various location of the building facility or infrastructure to be built. A construction project often involves few one-off activities and many repetitive activities performed more than

one time in different locations. A basic feature of building production is the space dimension, which should be taken into account for construction model creation. The movement of resources through the project, or the workflow, is, in fact, a basic planning issue. A suitable instrument suggested by researchers and practitioners for planning and scheduling a construction project is the time / space diagram, or flow-line chart (Peer, 1974, Selinger, 1980, Russell and Wong, 1983; Kähkönen, 1994), in which activities performed by resources are plotted as lines or other geometrical shapes against location and time (figure 2.4). Concerning this time / space scheduling approach, researchers have proposed many similar methods, that can be classified as Line of Balance for Projects with discrete space units, like floors of a high – rise building, factory buildings of an industrial plant, housing projects, and Linear Scheduling Method for continuous space projects, like highways and pipeline networks, which are actually time – space chart based (Harris, Ioannou, 1998).

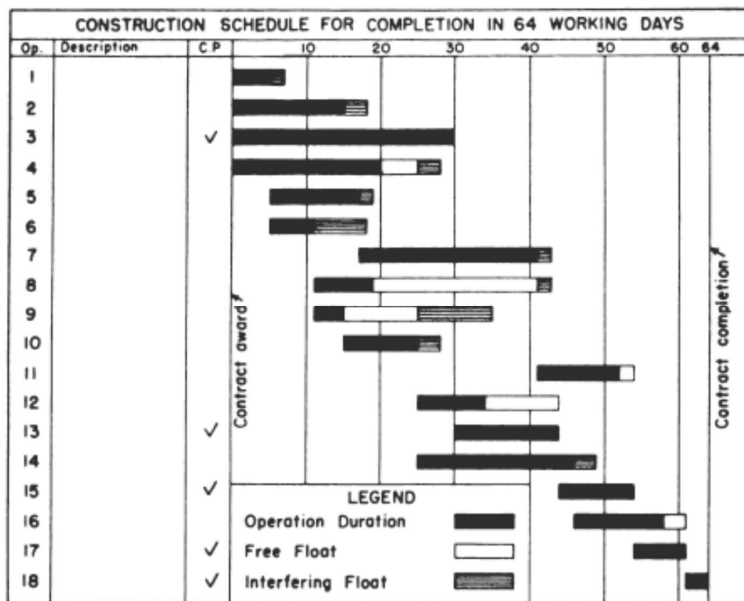


Figure 2.2: Gantt Chart (from Fondhal, 1961)

2.1.4 Safety management and project management

Safety Management is a fundamental process of construction Project Management to achieve project success, and the Health and Safety plan constitutes the basic documentation for the safety of construction project operations. The Health and Safety Management process includes all activities to be performed by the owner and by the contractor which can realize safety policies and objectives to ensure that the project is planned and executed preventing accidents, which can cause personal injuries or even fatalities. Project Safety Management consists primarily that the conditions of the contract, and of the Health and Safety Plan (if available), are carried out to assure the safety of both those working on site and those who are in the vicinity of the project (PMI, 2007). The Health and Safety plan identifies the strategies and procedures to be used in the project with the aim of creating a safe working environment for construction operations (APM, 2006). Therefore, a safety – oriented schedule should be included in the Health and Safety plan (EC, 1997).

Project safety management applies to all aspects of project management, and in particular to Project Time Management, as safety dependencies between activities in the project schedule can be of capital importance in preventing accidents and hazard creation. The safety specialists, or health and safety coordinator as defined by the well-known 92/57/EU directive, should develop a safety-oriented project schedule and has to evaluate the contractor's schedule to assure that provisions of the Health and Safety Plan are implemented in the forecasted work flow of construction activities. In particular, hazard protection can be delivered analysing safety dependencies between activities and activity interferences that can generate hazards, and time – space conflicts due to errors in workflow management or congested areas. In fact, some construction sequences have no technical interdependencies but, due to the proximity of the work areas, congested spaces, or safety issues, may cause injury risk to the crews (PMI, 2007). Therefore, construction project scheduling can be considered a fundamental component of safety design of the project execution stage, on site.

Surely, construction project safety performance depends on actual implementation of safety devices and procedures, but the relationship between project scheduling and construction safety is symbiotic, as the improvements in one generally result in improvements in the others (Veteto, 1994). Also, better safety management has positive impact on productivity (Shan, Goodrum, Zhai, Haas and Caldas, 2011). Therefore, safety-oriented scheduling, meaning the assurance of health and safety of workers in production planning, is a fundamental component of a process-oriented construction schedule.

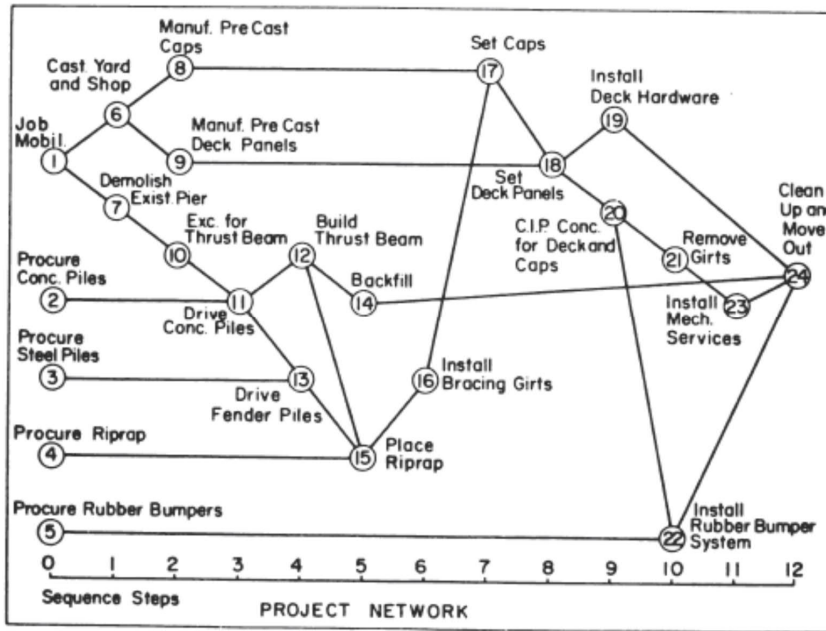


Figure 2.3: Portraying network logic for AON network (from Fondhal, 1961)

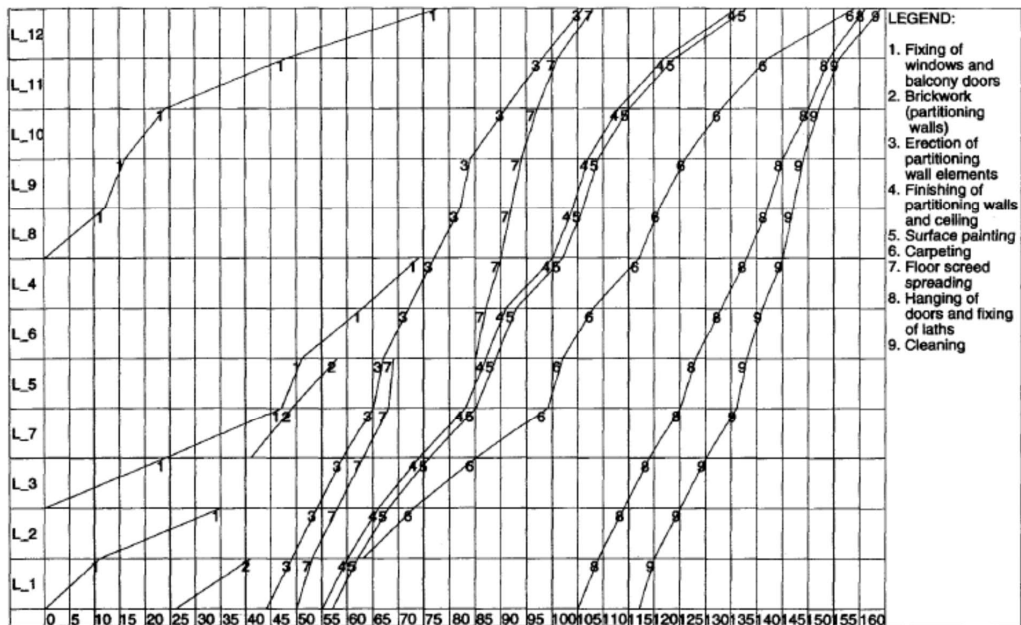


Figure 2.4: Location versus time schedule representation (from Kähkönen, 1994)

2.1.5 Quality of construction schedules and scheduling phases

The word “quality” means the standard of something as measured against other things of a similar kind (Oxford dictionary), and originates from Latin “qualitas”, translation of Greek “οποῦτα-οποιotes”, meaning “of such a kind”. In manufacturing, quality means a measure of excellence or a state of being free of defects, deficiencies and significant variations. It is brought about by strict and consistent commitment to certain standards that achieve uniformity of a product in order to satisfy specific customer or user requirements. ISO 9000:2015 standard defines quality as the degree to which a set of inherent characteristics of an object fulfils requirements, where a requirement is a need or expectation that is stated, or generally implied or obligatory. An organization focused on quality promotes a culture that results in the behaviour, attitudes, activities and processes that deliver value through fulfilling the needs and expectations of customers and other relevant interested parties. The quality of products and services includes not only their intended functions and performance, but also their perceived value and benefit to the customers (ISO 9000:2015).

Therefore, quality is understood as the level of accomplishment of product and processes to performance requirements. In construction projects the measure of quality performance is a complex task and, in general, construction projects are complex projects. Quality of the project is the degree to which a set of inherent characteristics fulfils the project requirements. Project quality management embraces all phases and parts of the project from the initial project definition, via the project processes, the management of the project team, the project deliverables and the closure of the project. Management of quality is based on the participation of all members of a project team who should regard quality as the foundation of the project, with the aim of ensuring customer satisfaction and, as a consequence, long-term business success (IPMA, 2006). A Quality Management System comprises activities by which the organization identifies its objectives and determines the processes and resources required to achieve desired results (ISO 9000:2015).

The quality assessment of a construction schedule can be a challenging task for project stakeholders. Quality can have multiple meanings, and the approach to the quality assessment of the scheduling process has to deal with the two main goals of the main player in the construction process, the owner/client, concerning the final built product: the fulfillment of needs and the adequate level of performances. The first suggests that quality means those features of the product, which meet customer needs and requirements, thus aiming at providing customer satisfaction. The second suggests that quality is related to freedom from defects, i.e. features that require rework or result in product failures and, again, customer dissatisfaction (Juran et alii, 1999).

The construction schedule is a document that integrates the planned work of the project, the resources necessary to accomplish the project and the associated costs. Therefore, the schedule should be the focal point of the project management of construction. Schedule quality, indeed, should play a major role in project management (Griffith, 2005; GAO, 2012).

The schedule provides a service to the project that no other project management methods can provide. The production of a quality schedule and its maintenance through the project is a most worthwhile investment (Callahan, Quackenbush and Rowings, 1992). Many are the purposes of a construction schedule, and the level of compliance to these purposes is a first understanding of the schedule quality.

Callahan, Quackenbush and Rowings (1992), indicates the following five purposes of a construction schedule:

1. Prediction of total project duration:
 - a. contractor can adjust crew size, equipment and shifts to speed or slow progress;

- b. owner's consultant can estimate the times of the design and building phases to complete the project when needed by the owner.
2. Prediction of start and finish of specific activities:
 - a. Subcontractors can have information concerning their involvement on site;
 - b. Contractors can expose and adjust conflicts between trades and subcontractors.
3. Control of a variety of resources:
 - a. plan of the cash flow for both owners and contractors.
4. Evaluation of the effects of changes on project completion and costs:
 - a. measure of delays and time extensions (in an updated schedule);
 - b. notice of time extensions, claims and additional costs because of acts of God or extra works.
5. Record of the project progress.

Feasibility and predictability of the schedule can give further understanding of the quality concept of a construction schedule (Kenley and Seppänen, 2010). They can give a measure of the effectiveness of the model of the planned production process. A feasible schedule minimizes the need of project control on-site as minor deviations can be easily recovered and major deviations can be recognized timely giving time for reaction. Quality scheduling produces feasible schedule, meaning with no unrealistic assumptions as for instance: sudden modification of production rates; availability of resources; weather effects on productivity; technological constraints; work planned in holiday season.

Kenley and Seppänen (2010) indicate the following items for a feasibility check of a schedule.

1. Quantities and task contents: correct estimate of production and task duration in each location.
2. Work flow:
 - a. Work continuity and wasted time of tasks and trades;
 - b. Buffers between tasks and locations;
 - c. Interference: time-space conflicts of crews.
3. Resources:
 - a. crew composition and availability;
 - b. resource allocation features (peak, time, locations).
4. Process logic: technological constraints and building logic.
5. Holidays and delay allowance.

Therefore, the construction schedule quality can be defined as the level of fulfillment of a certain set of requirements; those are relating to i) presence of construction knowledge, ii) processes for schedule production and management, and iii) needs of construction project management and project control.

The level of detail of a schedule and the project scheduling phases play an important role in schedule quality. In fact, the improvement of plan reliability is pursued in the Last Planner system of Ballard (2000) by taking action in the several phases and levels of the planning and scheduling process (Lean Construction Institute, 2007). Traditional project scheduling processes classify schedules into two main classes related to level of detail: the master schedule and the detailed schedule.

The Master Schedule is the most complete schedule for a construction project, it is a summary level project schedule that identifies the major deliverables and work breakdown structure components and key schedule milestones (APM, 2006; PMI, 2013). The Master Schedule covers all construction phases and items that are not strictly construction related, such as design, procurement and financing deadlines and, project approvals or reviews by local authorities. Generally, the owner's project team develops the Master Schedule, while the General Contractor develops the detailed schedule upon the award of contract, and submits it to the owner for approval.

The GAO Schedule Assessment Guide (GAO, 2012) defines three levels of schedules: summary, intermediate and detailed. The summary schedule is the highest level and provides a strategic view of the activities and milestones necessary to start and complete the project. The intermediate schedule includes all information displayed in the summary schedule, and shows the key activities and intermediate level milestones that represent the needed steps to achieve the high level milestones. The detailed schedule lays out the logically sequenced activities, which show the day-to-day effort to reach project objectives. A similar hierarchy of schedules can be found in the Italian regulation for public works, where the intermediate schedule is mostly safety– oriented (see paper VII).

The Practice Standard for Scheduling of PMI (2007) defines the following schedule levels.

1. Level 1: Executive summary, usually only one page that will include the major contractual milestones and summary level activities.
2. Level 2: Management summary, usually four to five pages that will include the level and report on similar activities by area or capital equipment.
3. Level 3: Publication Schedule (usually Project Control Schedule). This is the level of detail used to support the monthly report. It includes all major milestones, major elements of engineering, procurement, construction and start-up.
4. Level 4: Execution Planning. This supports the construction teams in their overall planning and can coincide with the Three Week Look-ahead Schedule. All activities of over a week's duration should normally be shown.
5. Level 5: Detailed Planning. This schedule supports the short term planning for the field, normally for those activities of less than one week duration.

The Project Management Body of Knowledge (2013), also proposes a simpler three level schedule definition: the Milestone Schedule, the Summary Schedule and the detailed schedule.

Ballard (2000) proposes a scheduling process articulated into four levels of detail (i.e. Master Schedule, Phase Schedule, Look-ahead Schedule and Weekly Plan). The Last Planner planning cycle (fig. 2.5) comprises: the master schedule covering an entire project, the detailed phase schedule emerging from collaborative planning, the look-ahead plan with constraint analysis and the weekly work plan with measured percent plan complete (Lean Construction Institute, 2007). These four hierarchical levels can be used also in the context of the combination of the Last Planner System and Location-Based Management System (Seppänen, Ballard, Pesonen, 2010).

The Master Schedule should include high-level milestones and summary activities. It is the output of the pre-planning phase and should be based upon an overall Location Breakdown Structure (on a building and floor level of detail), and on available productivity rates and quantities to evaluate the required production rates, and activity duration. Master schedule is used as the baseline schedule, and it is not used to manage production (Seppänen, Ballard, Pesonen, 2010).

The Phase Schedule is a detailed schedule usually developed together with subcontractors. Resources' availability and capability are well known by developers and, therefore, the objective of phase scheduling is production planning, scheduling and control. While a typical master schedule can include an average of 20 – 30 tasks, the phase schedule can include a fully developed activity network and/or flowline chart, the Location Breakdown structure and all the needed detailed tasks (Seppänen, Ballard, Pesonen, 2010). As a rule-of-thumb, to have maximum control we should have maximum detail (Samad, 1998). The development of a CPM – based schedule for large, complex projects can result in thousands of activities. For small to medium-sized projects the schedule can have from 100 to 1000 activities for better control (Samad, 1998). Even so, it is thought that to maintain the capability of transferring information, the number of activities should be, if possible, limited. Seppänen, Ballard and Pesonen (2010) argue that in this phase

workflow can be optimized by looking at the bottleneck trades with the lowest production rate, therefore increasing or decreasing resources and changing network logic, if needed.

Ballard (2000) indicates that the Look-ahead Schedule can have a time span of 4-6 weeks, and expands phase schedule activities into work assignments. As the number of scheduled items can be high, thus creating difficulties in the reading schedule diagrams, it is usually displayed as a bar chart or checklist of planned and completed work assignments, which can be updated on weekly basis.

The Weekly Plan is the lowest level of detail of scheduling and can be developed as a bar chart or checklist of planned and completed work assignments. The weekly plan has a high importance related to the social process of planning, communication and commitment at the crew, task and location levels (Ballard, 2000).

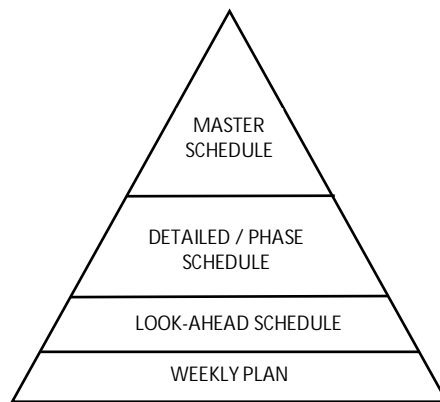


Figure 2.5: Schedule hierarchy (modified from Lean Construction Institute, 2007)

In the Italian construction sector the Public Works Regulation indicates three different level of detail of the project schedule (Italian Code of Contracts, 2016). The master schedule is delivered by the designer or project manager. Master schedule has the objective of indicating the total project duration for contract purposes, and the feasible productivity that must be developed by the contractor on site. Then, the owner's safety consultant develops the safety-oriented construction schedule. The well-known European Directive 92/57/UE on construction safety has introduced the safety coordinator, a professional which has the task to design the building site safety in the design phase, and to control and co-ordinate health and safety provisions and actions in the execution phase. As construction works' safety can be implemented mainly through construction planning and scheduling, an important component of the owner's Health and Safety plan is the safety-oriented project schedule. The owner's safety-oriented project schedule sets the safety requirements of the building project that must be satisfied by construction process. Generally, to avoid confusion and misunderstandings, the safety-oriented schedule become the owner's schedule in the design and bidding phase. After contract award, the general contractor develops the detailed schedule, and submit it to the owner's works supervisor before the commencement of works on site. Contractor's schedule must satisfy the requisites indicated by the owner in both schedules, concerning production process safety and productivity.

Griffith (2005) and the guide of the United States Government Accountability Office (GAO) report that there is a significant relationship between good scheduling practices used early in the project life cycle and the ultimate success of the project (GAO, 2009). Quality of the scheduling process, quality of the schedule itself and quality in project control can play an important role in the achievement of project success and can

represent key processes of construction project management. Little research work has been performed concerning quality in the scheduling and controlling process, though a good quality project schedule can be one of the key factors of construction project success.

The aim of this dissertation is to understand quality in the scheduling process, in the construction schedule and in project control, and to propose methods and approaches to improve quality in these processes and products of construction project management. Construction schedules are considered mostly at a Master Schedule level or at a Phase level.

2.1.6 Health and safety-oriented construction schedules

Project scheduling has also an impact on safety (Larsen, Whyte, 2013, Saurin et alii, 2004). In Europe, directive 92/57/EU (Temporary and mobile construction sites) requires an health and safety plan, and Suraji et al. (2001) found the planning and control failures related both to safety and production itself were major contributing factors to accidents in construction sites in the UK. In the U.S.A. Hinze and Wilson (2000) has consistently found that pre-project and pre-task safety planning are among the critical measures required to achieve a zero accident target. Therefore, the inclusion of health and safety factors in the construction schedule improve schedule quality and its process-oriented requisites. Safety oriented scheduling should include safety dependencies between activities to avoid hazard creation and time/space dependent conflicts between activities (Akinci et alii, 2002).

Veteto (1994) indicates that there are five project schedule – based factors highly correlated with a better safety performance. The factors are the following: a) the use of computer-based logic networks and resource-loaded schedules; b) the frequent updating of project schedules; c) the holding of coordination meetings often, thus maintaining good communication with all subcontractors; d) the holding of coordination meetings with subcontractors before the commencement of construction; and e) maintaining the project on-schedule.

Kartam (1997) presents a proactive safety environment, termed IKIS – Safety Integrated Knowledge Intensive System, for construction safety and performance control. The IKIS system is based on the three E's of safety: engineering, education and enforcement. Engineering means to perform specific safety actions such as substituting hazardous materials with less hazardous ones, using warning devices and prescribing protective equipment. Education means the use of the proposed system as a teaching and training tool. Enforcement means to follow safety laws and regulations. The objectives of the research are to provide contractors with a tool to plan the safety measures and to provide owners with means to review a contractor's safety plan and monitor performance during construction. The proposed system develops a database system of safety and health standards and recommendations for project activities and integrates the safety and health information into the critical path method CPM – based project schedule. Activities of the schedule can be classified in explicit and implicit activities. Explicit activities are for instance safety milestones (e.g. "install first aid station"), while implicit activities have a link with the safety information database and are highlighted with a message "flag".

Ballard (2000) indicates that a waste factor in construction is the lack of safety, therefore a safety – related requirement of a construction schedule is of capital importance. Nevertheless, the essence of a safety – oriented schedule is in avoiding time-space conflicts (Akinci et alii, 2002; Ciribini and Rigamonti, 1999, Sacks, Rozenfeld and Rosenfeld, 2009) and the well known "3S" rule-of-thumb by Callahan, Quackenbush and Rowings (1992), meaning safety, space and structure. Therefore, the essence of a safety – oriented

requirement for a construction schedule is to consider the spatial dimension of scheduling. The basic method suggested by researchers and practitioners for time – space project modeling is the linear scheduling method, flow line or linear planning, integrated with a network model (Kenley and Seppänen, 2010; Russell, Tran & Staub – French, 2014, Ciribini and Rigamonti, 1999).

Saurin, Formoso and Guimaraes (2004), present an innovative safety planning and control model (SPC), that integrates safety management to the production planning and control process, based on the concepts and principles used in construction production scheduling and control, particularly the Last Planner System by Ballard (2000). The integration of safety in construction planning and control takes place in three hierarchical levels: long-term planning, look-ahead planning and short-term planning. In long-term safety planning for each construction phase (e.g. bricklaying) a plan is produced using preliminary hazard analysis. In look-ahead safety planning a three-week production schedule is developed with the aim of the identification of safety constraints. In short-term planning the workers' commitment for one day and one week is identified and safety measures are discussed. In daily meetings safety and production plans are re-evaluated and the client provides a work permit. Safety control is performed through performance indicators and workers' participation interviewing groups of workers. The study indicates that long-term safety plans should be improved with the discussion of potential risks and should be systematically updated.

The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six type of spaces required by construction activities were detected and each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur. Ciribini and Galimberti (2005) observed that the H&S Management has widely to deal with working areas and space conflicts. A schedule model should indicate crew workflow directions, space requirements, and spatial buffers between activities.

Yi and Langford (2006) observed that the work environment of construction sites varies according the progress of the project and therefore the schedule affects the occurrence of hazardous situations, and the estimation of possible hazards must be coordinated with the project schedule. Hazardous locations and high-risk time periods of the project can be predicted if a safety-oriented schedule is developed. Therefore, it is possible to reschedule the start time of high-risk situation so that risks are not concentrated during certain periods and at certain locations. The authors present a risk-assessment method based on activity processes, construction locations and environmental factors.

Cameron and Hare (2008) investigated the integration of health and safety with construction project planning and developed eight integrated management tools for project team. One of the tools is a safety-oriented construction programme including activities and milestones required for the management of health and safety risks. As the programme is a tool to measure progress against time and to make sure that things get done, or at least to help to identify a problem if things are not done, it is important to include and schedule safety related activities and milestones. Moreover, the schedule can be used to highlight major risks in different phases of the project. The same authors (Hare and Cameron, 2012) develop a gateway model of a construction project to best promote the effective integration of health and safety management into construction project planning and control.

The optimization of the sequences of crews (workflows and production rates) can be done by scheduling work locations. Daewood and Mallasi (2006) and Mallasi (2006) observed that lack of execution pace planning may disrupt the progress of construction activities. Also, spatial congestion can severely reduce the productivity of workers sharing the same workspace, and may cause health and safety hazards to workers. A Critical Space-Time Analysis (CSA) approach is proposed to model and quantify workspace congestion and a computerized tool termed PECASO was developed for workspace management.

Zhang, Teizer, Pradhananga and Eastman (2015) highlight safety and productivity poor performances of construction due to congested site conditions, and propose a method for automated visualization of workspace with BIM. Workspace modelling is based on five workspace sets and a conflict taxonomy.

In conclusion, safety planning is an important concept and viewpoint for understanding safety characteristics of the construction production process, and though industrial standards and many researchers have addressed this issue, there is a lack of structured planning and scheduling method for the development of a safety-oriented schedule, at the owner and contractor level.

2.2 Previous research

The study of previous research addressed many sources, such as books, journal articles, conference proceedings and standards, with the aim of understanding construction schedule quality. As presented in the following paragraphs, the study of previous literature has revealed three main lines of research corresponding to the three research questions:

RQ1 – What is schedule quality?

RQ2 – What is scheduling producing in terms of quality?

RQ3 - Can the activity network schedule model be process-oriented and quality-driven?

The three lines of corresponding research uncovered are the following:

- the understanding of schedule quality for construction projects;
- the search for a construction quality approach in project control;
- and the search for an adequate scheduling approach for construction process.

Quality improvement in these three lines of research can play an important role in the management of construction process, with the aim of reaching project success.

2.2.1 Schedule quality for construction projects

Research based on the understanding of construction schedule quality has revealed three main research trajectories:

- characteristic of scheduling process;
- quality of scheduling process;
- quality of schedules.

Characteristic of Scheduling process is related to scheduling methods, rules and approach, focusing on the development and implementation of industrial standards about the scheduling function. A trustworthy scheduling process is about quality specifications of the production process of construction

schedules, and schedule quality concerns the level of performance needed by a construction schedule (seen as a product). Really, between process and product quality the division line can be very difficult to draw, as the two concepts are strictly interdependent.

Characteristic of Scheduling Process

Computer-based project schedule preparation and analysis dates back to the development of CPM and PERT techniques in the late fifties of the last century (Malcom, Roseboom, Clark, Fazar, 1959; Kelley and Walker, 1959; Kelley, 1961; Fondhal, 1961). These network-based techniques were invented for a computer-based scheduling approach, but because of complex input/output procedures, soon non-computer approaches were developed with hand-made graphic diagrams. Since the updating process was "labour-intensive", these systems were mainly used for planning overlooking the controlling phase. Nowadays, the availability of personal computing resources has overcome these limitations and led to a proliferation of computerized project management systems. Though the availability of project scheduling tools has simplified the scheduling process and schedule maintenance, there is still a recognizable lack of scheduling knowledge in practical applications.

An industrial survey of CPM scheduling use in U.S. Construction Industry by Galloway (2005), revealed a remarkable need for standards in construction project scheduling. Nowadays, few industrial applications exist, like the "Practice Standard for Scheduling" by PMI (2007) and many others. In fact, industrial knowledge and applications vary nowadays with regard to guidelines, standards and recommended practices issued by Project Management Institute (PMI), International Project Management Association (IPMA), Association for Project Management (APM), AACE International and US governmental organizations.

Concerning industrial guidelines for project scheduling, the first edition of the Project Management Institute "A Guide to the Project Management Body of Knowledge" (1996) defines the Knowledge Area of "Project Time Management" as a subset of Project Management that includes the processes required to ensure timely completion of the project. Project Schedule is simply defined as "the planned dates for performing activities and the planned dates for meeting milestones". The Project Schedule is simply defined as "the planned dates for performing activities and the planned dates for meeting milestones". Also, the IPMA Competence Baseline (2006) includes in the Technical Competence elements the "Time & Project phases", which entail a description of the possible process steps with a clear reference to the use of "Critical Path Diagrams". In perfect analogy with the PMBoK, the ISO 21500 International Standard "Guidance on project management" (ISO, 2012), defines the subject group "Time" corresponding to the "Project Time Management". The time subject group includes the processes required to schedule the project activities and to monitor progress to control the schedule. The purpose of the process of the Develop schedule is to calculate the start and end times of the project activities and to establish the overall project schedule baseline. ISO 21500 does not require a separate process for planning schedule management. More recently, the APM Competence Framework of the Association for Project Management (2015) defines Schedule Management as "the process of developing and maintaining schedules for the work activities required to implement a change initiative".

The "Practice Standard for Scheduling" of the PMI (2007) confirms that a key to project success is to apply knowledge, experience and intuition to a project plan, and the attempt to execute according to the plan. Scheduling is one of the basic requirements of project management planning and strategic analysis, and has the purpose of providing a "roadmap" that represents how and when the project will deliver the products defined in the project scope. This can be achieved through a "Schedule Model" (PMI, 2007), a dynamic representation of the project's plan for executing the project's activities, developed by the project team's

applying the scheduling method to a scheduling tool using project specific data such as activity lists and activity attributes. A scheduling method is a system of practices, techniques, procedures and rules used by project schedulers and performed either manually or with a project management software, i.e. a scheduling tool that provides schedule components supporting the application of a scheduling method (PMI, 2007). The Schedule development process includes selecting a scheduling method and tool, incorporating project specific data within that scheduling tool developing a project specific schedule model and generating a project schedule. This process has the aim of producing a schedule model of project execution, which has to be regularly updated to reflect progress and changes. Scheduling process includes activity definition, activity sequencing, activity resource estimating, activity duration estimating, schedule development, schedule control (PMI, 2007).

The AACE International (AACE) Recommended Practice No. 14R-90 (Douglas, 2006) describes the roles and responsibilities of a Planning and Scheduling Professional during the various phases of project planning and schedule development, management and control, also establishing planning and scheduling guidelines for training and professional development. Scheduling is defined as the "process of converting a general outline plan for a project into a time-based schedule based on available resources and time constraints".

In the U.S., of capital importance, the GAO "Cost Estimating and Assessment Guide" (2009) describes recommended best practices for developing and managing capital program costs of projects using public funds. The guide focuses on project cost estimating, planning and managing. The GAO guide includes schedule quality among the major reasons for a project's success. Schedule provides a time sequence for the duration of project activities, and should integrate the logical relationship between activities, activity resources requirements and durations, and any constraint that affects their start and completion. The GAO guide indicates nine requirements useful to develop and maintain an integrated network schedule. In the E.U. the CEN Workshop Agreement CWA 16022 (2009) "Project Schedule and Cost Performance Management (PSCPM)" is the European standard that gives specific indications on the informative system entailed in project scheduling function. It should be noted that, with the exception of the previously cited AACE Recommended Practice, none of these previously cited standards is construction oriented.

Quality of Scheduling Process

Quality identification of scheduling process aims at developing the schedule production process in a way that the final product (the schedule) will have a set of inherent characteristics that will fulfil project requirements. The intended functionality of the schedule should be validated during the course of the project (De La Garza, 1990; De La Garza, East and Yau, 1990). The study of De La Garza et alii (1990) individuates three stages of the scheduling process which are needed for schedule analysis and validation:

- prior to the start of construction;
- during project execution;
- at project completion.

In each of these stages a validation of the schedule is needed. The validation can be conducted by owners and contractors, and Project Managers and Schedulers need to check if the schedule meets the requested efficiency requirements. The validation process prior to the start of construction entails the check of the following schedule characteristics: contract requirements; participation of major subcontractors; inclusion of special construction oriented activities; critical path and overall degree of schedule criticality. The validation

process during project execution entails: project control; schedule maintenance; detection of “in trouble” activities. The study does not address the third phase validation.

Zwikael and Globerson (2004) introduced a model for evaluating the quality of project planning called “Project Management Planning Quality (PMPQ)”. The model consists of the two following components:

- project manager’s know – how, including processes for which a project manager is responsible, derived from the PMBOK;
- organizational support offered by the performing organization.

The PMPQ model identifies 16 know-how processes and output, as well as 17 organizational support processes and products. The processes are grouped into knowledge areas, based on the PMI classification and on existing Project Management maturity model, nine Knowledge areas (from PMBOK) for Project Know-How and four Knowledge areas for Organizational support. The model is structured to convert all these variables into an overall quality indicator. To achieve this purpose, a relative importance, or weight, is assigned to each process. Equal weight is assumed for the two groups, Know-How and Organizational, and equal weight is also assumed for each Knowledge Area. The weight of a specific process within a certain area depends on the number of processes in that area. The PMPQ index, that evaluates the quality of a project planning process in the organization, is calculated as a weighted average of the 33 processes evaluated. However, the focus of the work is not on the scheduling process and it is not construction oriented.

The Practice Standard for Scheduling of the Project Management Institute (2007) describes the schedule development process good practices and components. The PMI also offers a professional credential for project schedulers, which is based on five knowledge domains: schedule strategy, schedule planning and development, schedule monitoring and controlling, schedule closeout and stakeholder communication management. Key points in the schedule development process are needed for scheduling quality: schedule components and data; schedule development process activity definition; schedule model characteristics; project control features. Scheduling process includes activity definition, activity sequencing, activity resource estimating, activity duration estimating, schedule development, schedule control. Key points in the schedule development process are the following:

1) schedule components and data:

- review of information relating to time management;
- correspondence of WBS and schedule activities;
- definition of the order of execution of activities;
- resource availability must be considered after the initial activity sequencing;
- activity duration must be set depending on resource availability and productivity;

2) schedule development process:

- activity definition;
- activity sequencing;
- activity resource estimating;
- activity duration estimating;

3) schedule model characteristics:

- milestones;
- early and late activity times;
- schedule logic and constraints.

4) scheduling for project control:

- baseline definition;
- schedule update and maintenance;
- actual progress and schedule variations
- corrective actions approval and documentation.

Hietala (2009) indicated a framework to develop schedules with better quality and to assess the quality of a developed schedule. General requirements for schedule quality at an upper hierarchical level of planning are the following: realistic, feasible, simple, make commitment, accurate and timely. A detailed planning quality assessment is performed in two steps. First, the "Planalyzer" (Fishman I., Levitt R., 2007), a commercial system by Ibico Inc., is used to assess detailed schedule quality at a network level. Then the detailed criteria are used for the detailed planning quality assessment. The detailed criteria are: decomposed from Work Breakdown Structure (WBS), explicit description, logical sequence, indicate predecessor relations, well evaluated estimates, sufficiently detailed for measurement and control, standardized, highlight critical tasks, flexible modifiable and updateable, communicative, resourced, buffered.

The Scheduling Maturity Model (APM, 2012) has the aim of measuring an organization's ability to implement and apply a scheduling process, with the aim of producing a good quality and robust schedule. The Schedule Maturity Model can be used for the assessment of a single project schedule or to benchmark the quality of the scheduling process through the organization, and it is based upon the definition of 28 attributes, classified into 7 requirements: process and toolset; structure and hierarchy; integration; resource / cost integration; risk; update and maintenance, environment. With the exception of the De La Garza et alii work (1990), none of the previous approaches is construction-oriented.

Quality of Schedules

Quality of schedules entails requirement specifications and performance metrics to define a quality schedule. Again, the aim of De La Garza research work (De La Garza, 1990, De La Garza, East and Yau, 1990) was a deeper understanding of how owners and contractors evaluate the quality of a construction schedule. De La Garza defined a subset of scheduling principles to enable a construction schedule evaluation process for subsequent automation. An automated system called CRITEX, written for the U.S. Corps of Engineers has the purpose of "critiquing" construction schedules from four perspectives: general requirements, logic, cost and time of the project and of the activities. The system also encompasses thirty-four provisions for schedule quality assessment.

Therefore, quality of schedules entails requirement specifications and performance metrics to define a quality schedule. Schedule quality assessment was the aim of the study of Russell and Udaipurwala (2000). Here the perspective on schedule quality assessment is related to construction strategy, "the plan of attack", plus the timing of activities. Russell identifies various indicators of schedule quality, grouped under several headings: accuracy and completeness, consistency with other planning documents, good

practice/workability and benchmarks for control. Abstraction and compliance with contract documents are quoted but not examined in the cited literature.

Relevant information and data contained in a construction schedule require a proper reviewing process. O'Brian and Plotnick (2006) describe the reviewing process of a submitted CPM construction schedule with a legal accountability approach. In particular, the legal aspects that are highlighted relate to the consequences of the review process and to the rights of each part of the signed contract. After this, five major components of a good quality schedule are indicated: scheduling software; activity characteristics; network complexity; construction logic; dates and calendars. Each of these five major components focuses on specific check points or system requirements. Twenty-four detailed check points are described. The aim of the review process is not to verify that the contractor can perform the contract work according to the plan of execution provided by the CPM, but that the project schedule is technically correct, and that logic and durations appear "reasonable". The contract management approach of the works of O'Brian and Plotnick (2006), and of De La Garza et alii (1990) is believed to be a limit on the proposed schedule reviewing process.

AACE International (AACE) Recommended Practices (Douglas, 2006; Douglas, 2009; Douglas and Gransberg, 2009) include the "Schedule Quality Analysis" (AACE Recommended Practice No. 14R-90) and a guideline for schedule constructability (AACE Recommended Practices No. 48-R06 and No. 30R-03). Schedule Quality Analysis means the checking of the schedule specification compliance, the verification of the schedule integrity (i.e. schedule mechanics and constructability) and the schedule validation. The guideline for schedule constructability, instead, entails a review process of a construction schedule, termed Schedule Constructability Review (SCR). The goal of SCR process is to assess whether the schedule is comprehensive and complete. Constructability can be defined as the use of construction knowledge and experience in planning, design, procurement and field operation to achieve overall project objectives (Douglas, 2006; Douglas and Gransberg, 2009).

The Practice Standard for Scheduling of the Project Management Institute (2007) has described the methods related to scheduling that are generally recognized as good practice for "most projects, most of the time". The PMI standard also defines a Conformance Index and a Conformance Index Assessment process to evaluate schedule quality. The conformance index identifies the degree of compliance of a schedule model to the PMI scheduling standard. The conformance index is based on the list of components that must be utilized to develop a minimally acceptable schedule model. The components can be divided into two categories, required components and optional components. The schedule model conformance assessment process is designed to support manual assessment. The process evaluates the actual schedule model by looking for specific component markers and indicators to determine which specific components are present. When a component is present in the schedule model a point is earned. The required components are divided into three classes:

- Pre-development, including 8 components about WBS ID, activity ID, project details, calendar, data date and milestones;
- Development, including 10 components about activity label, unit of measure, duration, relationships, start and finish date, float, critical path and baseline data date;
- Maintenance and status reporting, including 27 components about percent complete, update cycle, activity code, cost and efforts, constraints, earned value, resources, schedule risk and variance.

The GAO "Schedule Assessment Guide" (2012) describes recommended best practices for project schedules. The guide focuses on project schedule quality to help managers and auditors ensure that the project schedule is reliable. The GAO guide provides ten best practices associated with a high quality and reliable schedule, and identifies four characteristics of a high quality, reliable schedule:

- Comprehensive;
- Well-constructed;
- Credible;
- Controlled.

The US Defense Contract Management Agency (DCMA) has defined 14 well known metric points aimed at identifying potential problem areas with a contractor's Integrated Master Schedule (DCMA, 2012). The DCMA 14 point schedule metrics is a tool that supports schedule analysis to determine whether it is a realistic schedule or not, i.e. gives metrics for assessing schedule quality. An automated MS Project Macro developed by the agency can also perform the schedule quality assessment. The schedule metrics are the following:

1. Logic;
2. Leads;
3. Lags;
4. Relationship types;
5. Hard Constraint;
6. High Float;
7. Negative Float;
8. High Duration;
9. Invalid Dates;
10. Resources;
11. Missed Tasks;
12. Critical Path Test;
13. Critical Path Length Index (CPLI);
14. Baseline Execution Index (BEI):

The National Defense Industrial Association (NDIA, 2012), working group of Industrial Committee for Program Management, published the "Planning and Scheduling Excellence Guide (PASEG)" to provide the project management team, including new and experienced master planners/schedulers, with practical approaches for building, using and maintaining the project master schedules. The guide encompasses "Generally Accepted Scheduling Principles (GASP), 10 quality control steps to validate the Integrated Master Schedule and a list of metrics that can be used to assess schedule health. The PASEG guide first introduces the term "Schedule Health Assessment" as a quality control of project schedule and suggests the implementation of an automated schedule health assessment tool. The PASEG approach of Schedule Health Assessment is different from the procedure proposed in the following paragraphs, as it focuses only on the "mechanics" of the schedule, and it is not construction oriented. The same observation can apply also to the previously cited GAO and PMI guides and metrics.

Moosavi (2012) and Moosavi and Moselhi (2012, 2014) defined a structured methodology to assist owners in the evaluation and approval of the detailed schedule of contractors. In essence it is a checklist that covers a set of overall requirements for good schedules, concerning both development process and final

schedule. The methodology has been implemented in an automated computer application called "Schedule Assessment and Evaluation - SAE," developed to assist owners in the review of project schedules. The SAE performs schedule evaluation in three tiers:

1. Assessment of the schedule against industry recommended practices;
2. Job logic assessment of construction trades;
3. Assessment of construction productivity and of crew size considered for a number of commonly used trades in building construction.

The method is based on the evaluation of forty-eight criteria for the schedule health assessment including conceptual provisions as well as quantitative requirements. The criteria are divided into three major categories: contractual compliance, schedule development, and schedule components. In the first step of the research (Moosavi 2012), the criteria are classified in conceptual provisions and quantitative provisions, actually they are classified in eight obligatory criteria and forty complementary criteria (Moosavi and Moselhi, 2014). The SAE method has a strong contract management connotation (like in the De La Garza study), which is believed to be a limit in this dissertation. Anyway, only five of the nine preceding approaches are construction – oriented.

Schedule quality of construction project: research gaps

In summary, the study of existing literature concerning schedule quality of construction project, in its three components, characteristic of scheduling process and quality of scheduling and schedule, has revealed the lack of a comprehensive approach concerning schedule and scheduling in the construction context. Previous research efforts and standards have addressed the content of schedule quality and its control but with a generalization of the type of projects, or with a contract management approach, or neglecting the scheduling process.

1. Generalization of the type of projects. The schedule quality approach is generalized, i.e. it is not oriented to the construction sector but it is aimed at the quality of any type of project schedule (Zwikael and Globerson, 2004; PMI, 2007; Hietala, 2009; GAO, 2009; DCMA, 2012; APM, 2012).
2. Contract management approach. The approaches have the aim of quality checking against contract specifications, i.e. they are in the construction context but not production-oriented (De La Garza, 1990; De La Garza, East and Yau, 1990; O'Brian and Plotnick, 2006; Moosavi (2012) and Moosavi and Moselhi, 2012, 2014).
3. Neglecting the scheduling process. Actually, almost all existing guidelines and standards about schedule quality are control oriented, and do not sufficiently highlight the schedule development phase.

Actually, almost all existing guidelines and standards about schedule quality are control oriented, and do not sufficiently highlight the schedule development phase. Moreover, few considers the building and construction dimension of the production process and most of them have a strong legal accountability connotation.

2.2.2 Construction quality approach in Project Control

Production Control consists of processes that are related to the coordination of all aspects of the production process such that the stated conditions pertaining to the production process itself are satisfied (Melles, Wameling, 1993). The measurement of the performance of a construction project can be achieved through technical testing and professional observations, and through the use of metrics such as Key Performance Indicators (KPIs). KPIs are measures of success that can be used throughout the project to ensure that its progressing towards a successful conclusion (APM, 2006). KPIs are intended to represent the health of the construction project and can be used to predict future project performance by means of an Information and Communication Technology (ICT) – based model, e.g. activity network or flow-line chart, and integrated with a proper controlling technique. In particular, project planning and control employ scheduling software for establishing a project's processes and duration (Murray, Arif, Lai, 2002).

The traditional construction control approach is basically project-oriented and aims at providing information needed for the project team to identify and correct problem areas related to quality, cost and work progress. Actually, in a construction project team these issues are treated quite separately and, generally, quality and safety control are often dealt with apart from cost and schedule control having two or three different responsible persons. Basically, this is because the main objective of construction project management is project delivery on time and within budget.

Traditional project control models are time and cost based. Time – based project control models aim at the progress measurement of a project. Main models are the bar chart / Gantt (fig. 2.6), Precedence Diagramming Method and Line of Balance technique / flow-line. Concerning time - oriented control methods, at least six KPIs can be defined in the area of time performance, related to time consumption and project completion, critical activities, construction logic, project location and resource productivity.

Earned Value Method (EVM) is the main tool that accomplishes traditional time/cost project control. The basic concept of Earned Value Management System is the focus on the integrated time/cost project control, and the subsequent definition of project KPIs for a quantitative approach for project monitoring, controlling and forecasting. The core tool of the EVM is the Work Breakdown Structure (WBS) (figure 2.7), that is the structure of the project information integration system (Moder et alii, 1983, Rasdorf and Abudayyeh, 1991). The EVM (ANSI/EIA, 1998) is a cost planning and programming tool that gives information about budgeted cost, actual cost and earned value related to the time of project development. Performance measurement of project status is mainly performed through the following KPIs: time and cost variances (and their ratio); project performance indexes, in addition to ordinary time-related KPIs.

In addition to time and cost project objectives, the project management “iron triangle” entails scope and quality (Atkinson, 1999). Generally speaking, quality can be defined as the fitness for purpose, while more stringent definition is the degree of conformance of the outputs and process (APM, 2006). In fact, it is well known that quality can be defined as the level of accomplishment of a product or a process to a set of performance requirements (ISO 9000:2005). ISO standards define quality as the degree to which a set of inherent characteristics fulfill requirements. Quality assessment in construction can be divided into three main components: quality of products, quality of design and quality of processes (Bragadin, 1999).

Quality of the project is the degree to which a set of inherent characteristics fulfills the project requirements. The risk of ignoring quality is that of not achieving the project objectives (IPMA, 2006). Project Quality Management includes all the processes and activities that determines quality policies, objectives, and responsibilities so that the project will satisfy the needs for which it was undertaken (PMI, 2013). Project Quality Management works to ensure that the project and product requirements are met and validated. There are four main processes concerning quality management: quality planning, quality assurance, quality

control and continuous improvement. Quality control consists of different sub-processes: inspection, testing, quality measurement. The aim of quality control is to verify that the project deliverables conform to specification, are fit for purpose and meet stakeholder expectations (APM, 2006). The intended quality approach of project control is the understanding of the role of quality and its development in project scheduling of construction.

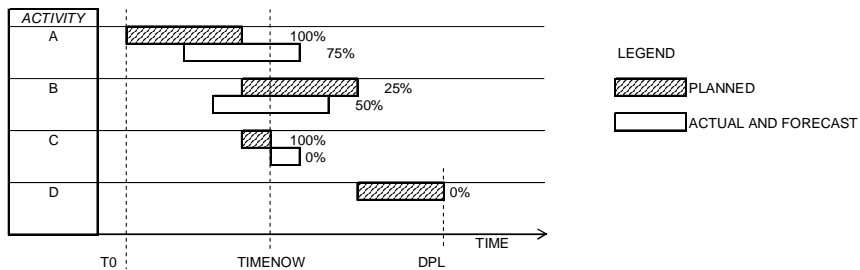


Figure 2.6: Control Bar Chart

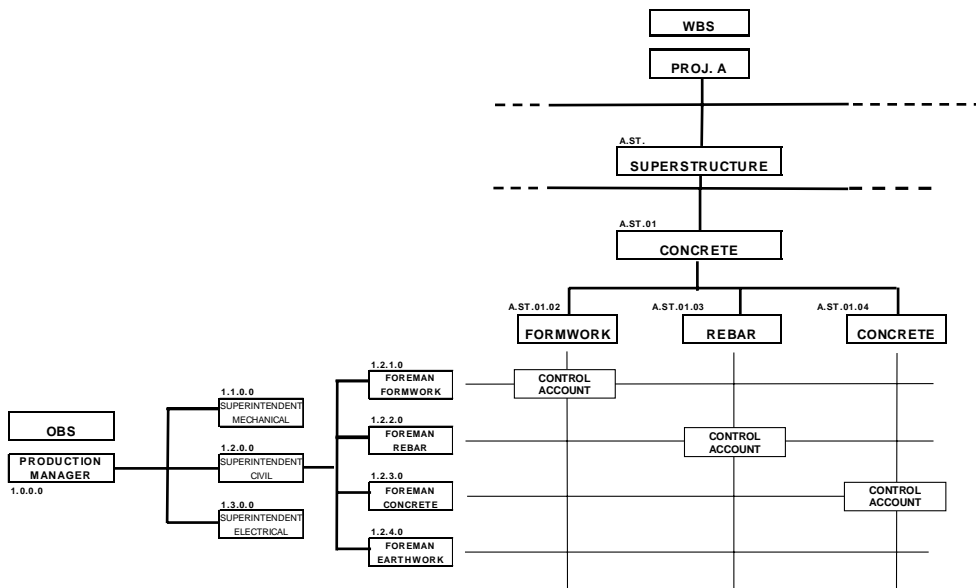


Figure 2.7: WBS: Work Package Structure approach (Rasdorf et alii, 1991)

Quality of products can be pursued mostly with the well-known performance approach. Also, the design documents can be evaluated in this way. In the design and construction phases, quality assessment can be performed on the basis of ISO 9000 series quality assurance systems. However, for construction

projects, the measure of quality performance can be a complex task, as most of construction projects are complex. While for time and cost it is easy to define some quantitative indexes to measure time and cost performance and so easily define some relevant KPIs, it is much more difficult to quantify and measure quality performance of a construction project and development related to quality meaningful KPIs.

In addition to the well-known ISO 9000 approach to quality systems, three approaches aimed at the definition of quality KPIs are presented. They are derived from existing international standards and pertinent literature. The standards are the following: that of the UK Minister of Construction; that of the Construction Industry Development Board of Singapore; that of the American National Cooperative Highway Research Program (NCHRP).

The Minister of Construction of the United Kingdom (2000) identified six KPIs: cost, time, quality, health and safety, business performance and change orders. The KPIs Working Group defines the quality KPIs basically as the frequency of defects in the end product. The Group assumes that quality in construction is subjective and means different things to different process operators, and that there is no objective recognised method of measuring quality in construction industry. So, the aim of the quality KPIs is to improve the visibility of quality issues on construction projects through the measurement of "Quality Issues". A "Quality Issue" is defined as an issue that affects the project so that work needs to be redone, modified or compromised to a lower standard than originally agreed. Therefore, the KPIs measure construction quality recording all quality issues on all elements within the project from the outset of the project. At the operational level, the KPI for quality is the number of quality issues, while at the project / headline level, the Quality KPI is called Defects KPI and it is recorded using a scoring system with the score of 10 for a product/element apparently defect free and a score 1 for a totally defective product. It is worth mentioning that in this approach there is another quality – related index which is Client Satisfaction, divided into four subcategories, each with a score from 1 to 10. In fact, from a Total Quality Management standpoint, Client Satisfaction is an important quality-related element. This indicator measures how satisfied the client is with the finished products and with the service of the contractors using the score in the 1 to 10 scale, with 10 meaning totally satisfied, 5/6 neither satisfied nor dissatisfied and 1 totally dissatisfied. At the operational level, the KPI measures how satisfied the client is with certain client - specified criteria, using the score of the 1 to 10 scale, but weighted together to determine their level of importance.

About the definition of KPIs for Construction project control, Kumaraswamy and Thorpe, (1996), added to time, cost, quality, and safety KPIs, the following KPIs: environmental impact, client and project team satisfaction, and technology transfer. Kerzner (2011) reported the following KPIs for the case studies of Disneyland and Disney World construction projects: time, cost, scope, safety, aesthetic value and quality, with the last three being fixed values that could not be negotiated. Suk et alii (2012), for pharmaceutical construction projects, included only the following KPIs: cost, time, quality, safety and design/space efficiency.

Another approach is that of the Construction Industry Development Board of Singapore, that developed an objective quality measurement System for building construction called CONQUAS, which is now also used as a quality standard for ISO 9000 local enterprises quality certification (Building and Construction Authority, 2008). The CONQUAS system indicates criteria for measuring construction quality and determines to what extent a project satisfies those requirements, related to a representative sampling of the building. The quality metric is based upon a scoring system that considers Building Quality divided into three primary component areas: Structural works, Architectural works and Mechanical and Electrical works. The weighted system is a compromise between the cost proportion of the three components and their aesthetic value, as they relate to the following building categories:

- category A/B: commercials, industrial, institutions etc. (A: with central cooling system; B: without central cooling system);

- category B: private housing;
- category C: public housing;
- category D: landed housing (bungalows, semi-detached houses, terrace houses etc.).

The procedure to find the construction project quality index starts with the computing of the percent passing the inspection points, depending on sample inspections. This value is combined with other elements in the same component (e.g. formwork and rebar in structural works). The component total (e.g. structural) is weighted a second time based on the building category. The sum of the three component scores is used as the final building score, i.e. the quality index.

The third approach to quality index evaluation is the one used by El Rayes and Kandil (2005, 2006) in recent studies for highway construction aimed at facilitating the measurement and quantification of construction quality. The proposed approach is a development of the "Quality – Based Performance Rating System" of the American National Cooperative Highway Research Program (NCHRP) (Anderson and Russel 2001, Minchin and Smith 2001) for contractors' qualification, and beside the evaluation of organisational issues of the contractors, has the main goal of evaluating the final quality of the products of the construction process, with a performance-based approach. With the aim of evaluating the final product quality a set of quality indicators are proposed and classified with a performance – based Quality Breakdown Structure (QBS). A multi-objective automated construction resource optimisation system termed MACROS is proposed, entailing a time, cost and quality trade-off algorithm.

Kenley and Seppänen (2010) indicate that there is a direct relationship between the design of the production system and the quality of the work produced. Planning for quality has the goal of improving the quality of the process and of the final product. This can be achieved giving enough time for inspections and quality checks at the end of each production cycle, before the commencement of the succeeding one. The plan should ensure that there is time for quality control in the interfaces between different trades, and it is suggested of using the time provided by buffers in the different locations of the schedule. In addition, time for quality related activities like for instance concrete curing should be scheduled, and quality checks before starting of individual task should be planned.

Construction quality approach in Project Control: research gaps

The four approaches considered for quality control, namely ISO 9000, KPIs working group, CONQUAS of Singapore and quality index evaluation, develop a dedicated project control approach for quality. All of them can produce as outputs quality – related KPIs but with few possibilities of connecting them with project progress as measured by time and cost KPIs, especially because quality indexes are not process-related. The ordinary approach of planning for quality, meaning giving extra time or time allowances inside activity durations for quality control do not add a real quality value to planning. Therefore, there is a need for better integration of quality in ordinary time-cost project control processes to highlight the quality flow inside the process.

Quality control, at a project level, is not integrated with the traditional time – cost project control approach. Nevertheless, the risk of ignoring quality is that of not achieving the project objectives, and if the "iron triangle" rule for project success factor holds, quality should be evaluated with specific project – based KPIs with a time-cost similar approach. In addition, and assuming that project control process is based upon the schedule model, quality control should be delivered and highlighted through scheduling process.

2.2.3 Scheduling approaches for Construction Projects: a criticism of the activity network approach

The original development work on activity networks that led to Critical Path Method (CPM), Project Evaluation and Review Technique (PERT) and Precedence Diagramming Method (PDM) that started in the mid-1950s (Malcom, Roseboom, Clark, Fazar, 1959; Kelley and Walker, 1959; Kelley, 1961; Fondhal, 1961) has progressed and made many substantial improvements (figures 2.8; 2.9; 2.10). Scheduling models are created with networking techniques, like Critical Path Method (CPM), Precedence Diagramming Method (PDM) and Program Evaluation and Review Technique (PERT). An algorithm (deterministic for CPM or probabilistic for PERT) computes process total duration. The textbook of professor Harris (1978) is a complete work concerning the use of networking techniques for construction scheduling and has the merit of indicating the strength of Precedence Diagramming with the simple logic link between activities, the finish to start, in the construction context. Beyond this traditional networking approach the computer simulation approach, CYCLONE for instance (Halpin and Riggs, 1992) or STROBOSCOPE (Martinez, 1996), implemented with activity cycle diagrams, tried to overcome the limits of CPM based scheduling creating a probabilistic model starting from the basic components of activities, i.e. construction operations.

Advantages of project scheduling as a process model useful to manage projects are many, and good project scheduling practices and techniques are correlated with project success (Griffith, 2005). Though the main advantage of construction project scheduling is the process of scheduling itself, and the implementation of a continuous scheduling process is what really makes the difference in achieving project success, schedule quality can play a major role in enhancing the efficiency of the building construction process. In this context, schedule quality can be defined as the desirable level of understanding of the construction process transferred in the scheduling model. In fact, construction projects have very specific features in comparison to other projects, mainly because of the industrial organization of companies in the construction sector and because of the complex technology of building and construction works.

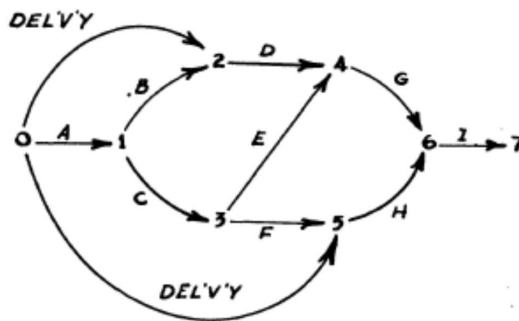


Figure 2.8: CPM: typical project diagram (from Kelley and Walker, 1959)

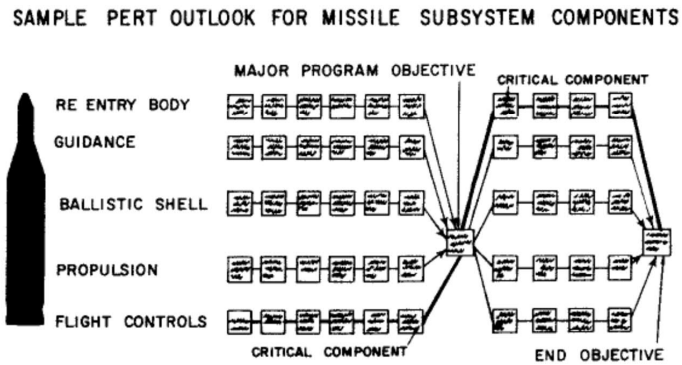
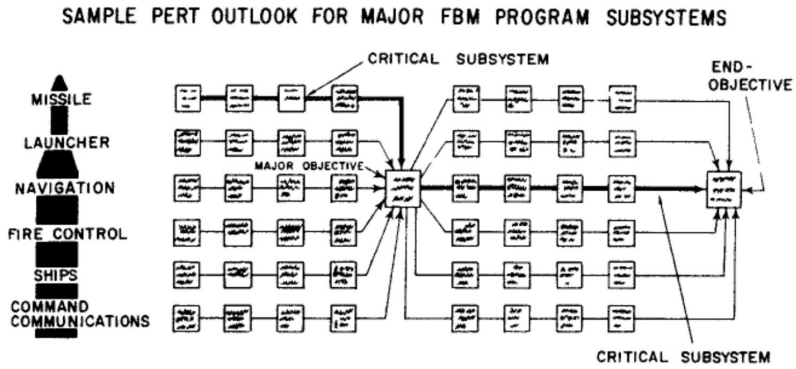


Figure 2.9: PERT: integrated outlook (from Malcom, Roseboom, Clark, Fazar, 1959)

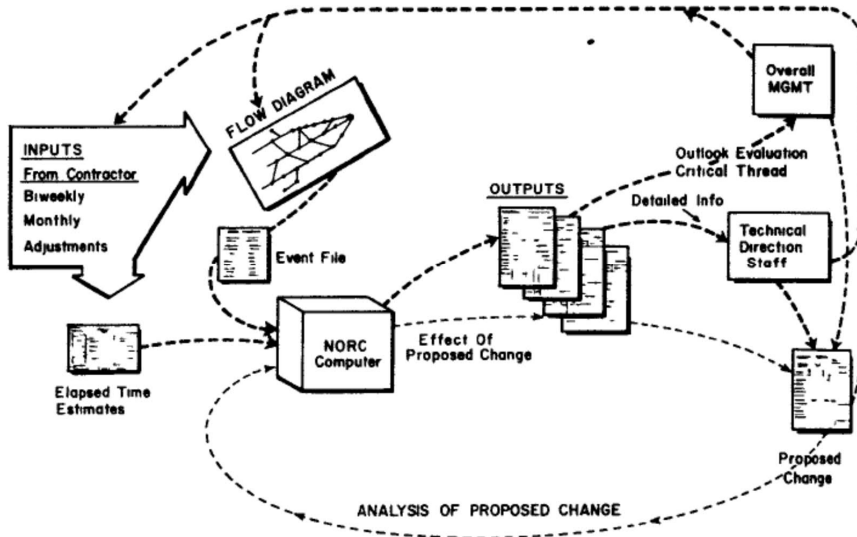


Figure 2.10: PERT system in operation (from Malcom, Roseboom, Clark, Fazar, 1959)

Researcher and practitioners understood the inadequacy of network analysis and related resource allocation techniques for a construction project since the early applications (Peer, 1974; Roderick, 1977; Birrell, 1980), and many improved and process-oriented planning and scheduling techniques have been developed. These methods are mostly based upon the Line of Balance technique (LOB) or flow lines (Kenley, Seppänen, 2010). Construction projects are characterised by repetitive activities performed by similar and scarce resources that finish these jobs successively (Su, Lucko, 2015). The developments in the U.S.A. of the Line Of Balance (LOB) can be found in the building construction of the Empire State Building by The Starrett Brothers Company (Kenley and Seppänen, 2010; Sacks and Partouche, 2010), and there is evidence of this production planning and controlling system in manufacturing before World War II. The Line Of Balance was developed in 1941 by the Goodyear Company as a graphic project control method, and next it was developed by US Navy Bureau of Aeronautics in the 1950s (Davey, 1974). Lumsden (1968) related the graphical method to the Activity on Arc activity network of CPM. The Line of Balance method is a diagram that represents space units in the vertical axis, and time in the horizontal axis. Project activities are represented by dual parallel lines, start and finish, that join the start and finish events of a barchart activity or of an Activity On Arc CPM network model of the process to be performed in one single unit (Arditi, Tokedmir and Suh, 2001). Linear Scheduling Method instead, was developed by Peer (1974) and Selinger (1980) with the name of production lines, the term Flow-line being coined by Mohr (as reported by Kenley and Seppänen, 2010). The Flowline is a diagram that represents activities plotted as lines in a time – space chart, therefore has a representation that is more suitable to Activity On Node, or Precedence Diagramming network (Su, Lucko, 2015). Concerning process-oriented scheduling approaches for construction projects, the following research works indicated “innovative” tools and methods in opposition with the “mainstream” graphical and network-based approaches.

Birrell (1980) recognized that there are two main components of construction project analysis and scheduling: work locations and resources. The main construction project characteristic is the need to follow a specific sequence of activities due to production technology and product structure, i.e. space constraints. Construction projects need multiple types of resources, with limited availability in time and quantity, which move inside the product, the building or the construction infrastructure, to perform their working activities. Another specific feature is the need of assuring resource usage continuity, but also permitting work interruptions due to a multi-project company environment or due to technical reasons. Many scheduling methods have been proposed in literature in order to improve construction project organisation with a scheduling model which addresses these two main issues, resource flow and space constraints.

Again, Birrell (1980) himself proposed a construction-oriented scheduling method based upon a matrix of work packages with work locations on the vertical axis, and times on the horizontal axis. The work locations are sequenced as they will be built on site, and the construction process is composed of many flow-lines, each consisting of a work crew moving through a series of locations. The queueing theory was used for the scheduling algorithm. The work crew is the basis for the scheduling model. In fact, construction productivity is based upon a construction crew, or squad, made up of various resources which co-operate to build the requested component. Birrell considered each work crew as a continuous flow of work.

Selinger (1980) created a flow-line based algorithm to optimize the work flow of crews. As crews perform activities from one space unit of the project to another, it is advantageous to arrange for such crews to work continuously, without interruptions, thereby preventing idle intervals of equipment and manpower. Russell (Russell and Wong, 1993) developed a construction management approach termed Representing Construction (REPCON) based upon an integrated scheduling system which coordinates a network logic, including generalized Precedence Diagramming logic links between activities (Finish to Start, Start to Start, Finish to Finish and Start to Finish), with linear planning or time – space charts. REPCON introduces different planning structures, i.e. activity types, which allow one to model time and space simultaneously. A planning structure is specified to reflect the work locations where instances of the activity occur, the order of

operations and various data about construction crew, work continuity constraints and interruptions, resource assignments (Russell, Udaipurwala, Wong, 2003).

Kähkönen (1994) developed a scheduling model, which focuses on the logic of building construction and activity dependencies. The main causes of activity dependencies in construction projects are due to resource types and work-area structure. The developed scheduling model aims at supporting strategic and early planning decisions and the systematic preparation of construction schedules. The construction project model consists of project-dependent and project-independent parts. The project dependent part consists of data for a particular project that the planner must define, particularly locations of the project and their sequence of construction, activities needed to build each location and available resources. Then, a specific knowledge – based procedure creates the project – independent part of the schedule model. The model has been successfully implemented and tested in the form of a computer program.

Riley and Sanvido (1995 and 1997) observed that current space planning in multi-storey building construction is limited to site layout and logistics, and they propose a space planning method that provides a logical order and priority for activities related to their needed spaces. Effectively, a construction planner needs to: (1) identify the space needed for activities; (2) define locations for these spaces on building floors; (3) develop a sequence of work that defines the order spaces are occupied; (4) identify potential spatial conflicts.

El-Rayes and Mosehli (1998) suggested that resource – driven scheduling accounts directly for crew work continuity and facilitate effective resource utilization. They suggested that resource – driven scheduling of repetitive activities requires the satisfaction of three constraints: precedence relationship, crew availability and crew work continuity. An optimization algorithm for project scheduling efficiency was presented. Harris and Ioannou (1998) focused on CPM multi-unit scheduling, and created a repetitive scheduling model that ensures continuous resource utilization with a flow view and a Precedence Diagramming Method (PDM) view of the model. The method was termed Repetitive Scheduling Method (RSM). Later, Yang and Ioannou (2001) proposed a scheduling method that focuses on practical concerns in repetitive projects, and implemented in particular the pulling effect in the continuity relationship between activities. It is believed that the RSM method fails to achieve its aim of providing a general model (Kenley, Seppänen, 2010). Arditi, Tokdemir and Suh (2001, 2002) integrated non – linear and discrete activities into Line Of balance (LOB) calculations and defined time and space interdependencies among activities such as a base concept for repetitive project scheduling. Kang et alii (2001) observed that in a multiple repetitive construction project, construction cost and duration are dependent on: number of work areas, proper crew grouping, size of work areas, frequency of repetition of each activity, and provided an heuristic approach to allow optimal construction planning.

Yi, Lee and Choi (2002) presented a heuristic method for network construction and development for repetitive unit projects, with the aim of minimizing total project duration by reducing idle time of resources and spaces. Actually, the heuristic changes the sequence with which crews complete the scope of work encompassed in each repetitive activity. This approach and general formulation has been applied in earlier and more accurate models (El Rayes and Moselhi, 1998) which guarantee a global optimum solution. Although, they presented an innovative way of displaying the schedule model, i.e. the plotting of the Precedence Diagramming network on a resource – space chart that creates a very communicative and location-based schedule.

Guo (2002) proposed to integrate computer-aided design with scheduling software for the dynamic identification of space conflicts on the jobsite. Work-space types are identified and time-space conflicts are studied. The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six types of spaces required by construction activities were detected and each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur. Ciribini and Galimberti (2005) observed

that the H&S Management has to deal widely with working areas and space conflicts. A schedule model should indicate crew workflow directions, space requirements, and spatial buffers between activities. The optimization of the sequences of crews (workflows and production rates) can be done by scheduling work locations. Daewood and Mallasi (2006) and Mallasi (2006) observed that lack of execution pace planning may disrupt the progress of construction activities. Also, spatial congestion can severely reduce the productivity of workers sharing the same workspace, and may cause health and safety hazards to workers. A Critical Space-Time Analysis (CSA) approach is proposed, to model and quantify workspace congestion, and a computerized tool termed PECASO was developed for workspace management. Kenley and Seppänen (2009, 2010; Seppänen, 2009) observed that locations are important in construction because building can be seen as a discrete repetitive construction process, a series of physical locations in which work of variable type and quantity must be completed. They also observed that the location-based methodology does not exclude Critical Path Method (CPM), in fact dependencies between activities in the various locations and between tasks (that are made up of activities of the same work item) are realized with CPM logic links. Construction projects are location – based projects (Kenley, Seppänen, 2010), where resources perform the same activity in different locations consecutively.

Choy, Lee, Park et alii (2014), observed that current construction planning techniques have proven to be insufficient for work-space planning because they do not account for needed spaces for activities. Therefore, a framework for work-space planning is proposed that categorizes activity spaces and includes 4D Building Information Model (BIM) generation for space identification. Zhang, Teizer, Pradhananga and Eastman (2015) highlighted safety and productivity poor performances of construction due to congested site conditions, and proposed a method for automated visualization of the workspace with BIM. Workspace modelling is based on five workspace sets and a conflict taxonomy.

Scheduling approaches for Construction Projects: research gaps

The study of previous work highlighted different research lines, mainly connected with a criticism of the activity network approach. The sole networking approach which leads to a schedule model based only upon an activity network, has been criticised by many practitioners and researchers. Koskela (1992), indicates three conventional managerial concepts that are detrimental for the management of construction projects (sequential project realization, lack of quality consideration and segmented control), but above all indicates the use of CPM – Critical Path Method based construction planning and scheduling. CPM – based scheduling and the other managerial concepts violate principles of flow process design and improvement leading to non – optimal flows and expansion of non value-adding activity. Network planning requires the division of flows into specific activities, which are organized into a sequence without considering the work flow, i.e. previous and successive activities and working locations. In case of activities being a complete work flow (e.g. elevator installation) the network plan the starting and finishing times but not the flow itself. Therefore, traditional network planning fails to support the planning of work flows of teams or materials, resulting in disruptive disconnects of these flows. In synthesis, the criticism of the CPM – based approach for construction scheduling address the following topics:

1. Project type: construction are complex projects, with multiple activities and with strong sequential constraints because of technology and contract-based and organisation approach.
2. Resources an space: in construction projects crews and space are scarce resources, and their constraints have to be taken into account for model structuring.
3. Work flow: resource and space usage are not linked in schedule model whereas in reality they are.

The proposed solutions to these issues are many and different authors propose different solution. Nevertheless, the following common research lines have been found.

1) Time / space charts. They are derived by Line of Balance (LOB) techniques and flow lines (Kenley and Seppänen, 2010), where activities are plotted as lines or geometrical shapes on a system of two coordinates, time and space. Activities and set of construction operations can be grouped together and process duration can be computed, mainly from geometrical understanding of the diagram. The following works belong to this research line. The work of O'Brien (1975) highlights the benefit of time / space charts in construction scheduling of high rise building project. The construction of the repetitive part of the project (typical floors) is performed through time/space charts termed Vertical Production Method (VPM), while CPM network is used for one-off activities of the project. The paper proposes also the integration of this graphic approach with CPM, and set the foundations of scheduling methods that take into account the workflow related to the workspace dimension. Later, O'Brien, Kreitzberg and Mikes (1985) compare VPM with CPM and use VPM to drive network implementation. Johnston (1981) describes the application of linear scheduling in transportation projects, improving the diagram-based method with cost control features. Stradal & Cacha (1982) improved the method giving insights on the principal organisation of the construction process, on the use of resources and on work – flow patterns. Flow – lines are compared with activity network models. Also, the work of Thabet and Beliveau (1994), termed HVLS – Horizontal and Vertical Logic Scheduling, belongs to this research line.

2) Linear Scheduling Methods, flow-lines and optimisation algorithms. The seminal works of Selinger (1980) and Birrell (1980), with the one of Ashley (1980) and Perera (1983), opened the research line of pursuing a more suitable scheduling method for construction project, beyond the critical path analysis. The idea is to use time / space charts to plot flow-lines indicating construction operations, and link this graphic representation of the project to an algorithm to compute total duration. These scheduling approaches consider that in construction projects there are always, at least, three constraints concerning: a) the scarcity of resources, i.e. construction crews work in building site in a limited number; b) the spaces where production is performed are also a scarce resource (to be considered explicitly); c) and finally the end product constraints because of physical causes, i.e. construction technology that needs specific logic links between activities. Russell and Caselton (1988), Reda (1990), Rahbar and Rowings (1992), Moselhi and El-Rayes (1993) and Hegazy, Moselhi and Fazio (1983) followed this research line and implemented scheduling algorithm with flow-line view of the project. A further evolution and treatment of the research problem can be found in Thabet and Beliveau (1997), El-Rayes and Moselhi (1998), and in the research work of Kang, Park and Lee (2001) and Vanhoucke (2006). On a slightly different research line are the works of Russell and Wong (1993) and Suhail and Neale (1994) that have the aim of integrating the CPM network with the flow-line approach. This research field has been investigated also by Harris and Ioannou (1998). Arditi, Tokdemir and Suh (2001), while Kähkönen (1994) investigated an automated expert system for project scheduling based upon construction principles. Kenley and Seppänen (2010) propose a complete Location-Based Management System (LBMS) to aim at production efficiency in construction, that integrates flowline and CPM-based algorithm and logic.

3) Project scheduling with a Lean Construction approach. The Lean Construction approach is addressed by well-known comprehensive work of Koskela (1992) and its application in the scheduling field of Tommelein, Riley and Howell (1999), Yang and Ioannou (2001), and Seppänen and Aalto (2005). Aside to this research lines stands the Goldratt's Theory of Constraints (TOC), known as Critical Chain Scheduling and Buffer Management (Goldratt, 2004; Rand, 2000; Steyn, 2000; Herroelen and Leus, 2001). Critical chain approach was investigated by several researchers, and surely some of its components (i.e. critical chain detection, use of buffers) give an interesting insight on project dynamics, but its shortcomings mainly concerning its management assumptions on buffers and critical chain activities have been highlighted by pertinent literature (Herroelen and Leus, 2001). Takt time planning, meaning the pace of production process

that best suits clients need, is another feature of lean approach to project scheduling (Frandsen, Berghede, Tommelein, 2013; Tommelein, 2017).

In summary, the proposed solutions aim at improving the network – based approach for construction project scheduling to take account for flow. The improvement necessitates different algorithm and software and may not be suitable in traditional contractual environment. Indeed, activity network is the conventional scheduling model in actual construction projects, and has proven to be very powerful technique (Arditi, Tokedmir, Suh, 2002) for work structuring. Therefore, the integration of a network based-model and a flowline and can still be developed further.

2.3 Summary of the previous research and its limits

The study of the previous research has highlighted specific features of quality in construction scheduling and its need for improvement. Concerning schedule quality as a specific focus area, it has been shown that the study of the characteristic of the scheduling process has revealed a remarkable need for scheduling standards. Actually, industrial standards exist, but only one of the eight cited is construction oriented. Concerning quality identification of scheduling process, only one out of the five studied approaches turned out to be construction oriented. In addition, concerning quality of schedules, only five of the nine evaluated approaches turned out to be construction oriented. Therefore, existing research works and industrial standards concerning schedule quality as a whole have revealed to be general and not specific for construction. This demonstrates the need for improvement with the aim of being construction oriented, i.e. there is a lack of quality standards for construction scheduling with the objective of understanding and properly modelling constructions projects. In addition to this, the study revealed that most of previous work has a contract management / legal approach that highlights the control phase neglecting the importance of the scheduling process in the sense of giving importance to the schedule development phase.

This need is reflected in the lack of structured methods for quality treatment and delivery in traditional methods of project control. In fact, concerning construction quality approach in Project Control, the traditional control approach generally aims at providing information related to the quality of activities, costs and times quite separately. Existing project control models are mainly time and cost based, and the detected existing quality control approaches need to be better integrated with the project control processes. If the quality management function should be fully integrated in project control, the schedule model should be able of bearing quality – related information of project activities. Project managers should have in progress and up to date information concerning time, cost and quality and their relation.

While quality in construction scheduling and project control has been rarely objective of research work, construction-oriented project scheduling has been studied by researchers for decades. Therefore, the study of previous research has detected many components of a construction-oriented project schedule. Mainly, a process-oriented project schedule in the construction sector should consider two basic factors: resources and spaces. A time – space chart, meaning the plotting of activities in a two coordinates system (time and space) is considered the most suitable graphic model to represent construction process. The basic method suggested by researchers and practitioners for time – space project modeling is the linear scheduling method, flow line or linear planning based on a time – space chart, completed with a scheduling optimization algorithm or simply integrated with a CPM-based network model (Russell and Wong, 1993; Kenley and Seppänen, 2010; Russell, Tran & Staub – French, 2014). This method and approach is believed to be, using Russell's own words, the definitive treatment for the construction-scheduling problem (Russell, Udaipurwala,

Wong; 2006). In addition to these proposed solutions lean process management issues have been considered of greater importance (e.g. work continuity constraints, workflow and workspace management, the elimination of waste –muda, takt time planning), and have been included in construction-oriented scheduling methods (Koskela, 1992; Ballard, 2000; Seppänen and Aalto, 2005; Kenley, Seppänen, 2010; Frandson, Berghede, Tommelein, 2013). The study of pertinent literature highlights as a main contribution to this research field the work of Kenley and Seppänen (2010). The Location-Based Management System is a flow-line based scheduling method that tracks the workflow of crews moving through a building or a construction infrastructure, and completing all their work location by location with repetitive activities linked to each other with a network logic.

In summary, the proposed solutions aim at abandoning the network-based approach though its wide spread use in actual construction projects. However, this widespread diffusion of network – based commercial applications for project scheduling can be a non-secondary reason for the poor quality frequently found in construction schedules, but also a strong point to start for the quality improvement process in scheduling. Therefore, this dissertation addresses mainly networking techniques and the search to improve their quality, understood as process-oriented modelling. The leading idea is not to create a method similar to LBMS, which is existing, but to improve the quality of traditional activity-network based schedule models. The knowledge of the LBMS encouraged the author to develop this research line. The dissertation proposes to improve scheduling with networking techniques by including in the schedule model the main components which are still missing: space and workflow, i.e. resources, and adding to the traditional network view and barchart view the innovative flowline view.

2.4 Aim of the dissertation

This dissertation has the aim of contributing to the understanding of the quality of construction scheduling. Three issues have been chosen: schedule quality, quality and project control, scheduling approaches, and three corresponding methods have been proposed. However, it is worth mentioning that the final goal of the whole research work is not to develop the best solutions to solve construction scheduling problems, but is to study quality in scheduling and project controlling, and to propose some possible research lines to better understand the needed quality for planning, scheduling, and controlling approaches in construction projects

The understanding of quality of schedules is achieved through the evaluation and definition of a set of related quality requirements. The definition of a set of quality items of construction schedules can help project schedulers to produce a good quality schedule and to perform an effective maintenance process of the construction schedule. Quality means also being process – oriented. The quality of the schedule model can be improved with a process-oriented modeling and having both the activity network structure and the flowline in the model. The proposed “Schedule Health Assessment” process quantifies schedule performance, thus enabling the project team to implement a proactive approach to construction scheduling. The basic concept behind this method and approach is that schedule quality can be defined as the desirable level of understanding of the construction process transferred into the schedule model.

The controlling phase of a construction project is focused on in this dissertation. It is suggested that quality understanding in construction projects, and quality creation process during project delivery, can be pursued through the implementation of a Quality Breakdown Structure (QBS), thus reporting a quality oriented project status in the project controlling phase, which can be seen, in most cases, as the level of achievement of project success, together with time and cost indicators.

Finally, the dissertation proposes the use of resource-space charts for activity network plotting (Yi, Lee and Choi, 2002), aiming at the improvement of the network-based schedule model of a construction project. A complete workspace management system is proposed, termed Repetitive Networking Technique (REPNET). REPNET is based upon a Location Breakdown Structure (Kenley and Seppänen, 2010) and an innovative resource-based scheduling algorithm. The resource-space chart use can improve location-based workflow tracking of resource movement through building site locations and therefore project control, while the REPNET algorithm aims at workflow optimization. A flow-line view can be plotted to enhance the fulfillment of construction safety – related space requirements.

3. Summaries of the papers

This chapter summarizes the main results of the papers. The summaries briefly highlight the purpose, research methodology, findings and contribution of each paper. The full papers can be found appended to the dissertation.

3.1 Paper I: Innovation in Construction Project Control

This paper is about innovation in construction project control, focusing on project control methods and approaches. The paper consists of a literature review of construction control methods, which have been classified in project oriented, or traditional methods, and process oriented, i.e. innovative methods. The qualitative research method is followed. The paper contribution is the review of various construction project control ICT – based methods and approaches, focusing on their principles for understanding the status of a project. The control methods have been categorized into traditional approaches, termed project oriented approaches, and innovative approaches, termed production oriented approaches. Control data from project control methods are analysed, and related types of Key Performance Indicators (KPIs) of the project are detected.

A construction project is a temporary production process composed by multiple sub-processes with the aim of creating a building or a civil engineering product. So project control has the aim of monitoring and controlling project progress in relationship with the final goal, while production control has the aim of driving the process or sub-process, conceived as a flow of materials, equipment, manpower, work and information, to be conformed to the production plan and quality specifications (Ballard, 2000).

The traditional approach to Project Control evaluates time data, or time and cost data to estimate the progress of the project and understand its status. This is the core of Earned Value Management (EVM). The management by exception, meaning basically to focus on project variances, is the result of the traditional approach. However, the “miracle” of the integration of scope, quality, budget, actual cost and schedule seldom takes place in real projects. This is mainly because the building process is not only a set of conversion activities, but also a group of process flows, i.e. the interdependence of parts in a flow of work, resources, materials, processes and information (Koskela, 1992). The production control approach takes this and other issues into account, like human resource behaviour and social process, to improve construction project performance.

The Last Planner System for production control is a production-oriented approach to construction process management introduced by Ballard (1998, 2000) in the construction industry. The Last Planner aims to achieve the lean goals of decreasing waste, increasing productivity and decreasing variability. The Last Planner approach is mainly based on the improvement of social processes in project organization, i.e. by trying to make planning a collaborative effort and improving the reliability of commitments of team members (Henrich, Tilley, Koskela, 2005, Koskela, Stratton, Koskenvesa, 2010).

Goldratt’s Critical Chain (CC) and the Theory of Constraints(TOC) and its direct application to Project Management, known as “Critical Chain Scheduling” (Goldratt, Cox 2004, Rand, 2000, Henrich, Tilley and Koskela 2005) addresses both project-oriented and production-oriented control processes. Critical Chain

focuses on the constraints of the project production that can prevent it from achieving its goals. Also, Goldratt (2004) argues that the principle reason for project overrun is certain typical human behaviour patterns. The main concept of critical chain scheduling is that the critical chain of activities, performed by key resources, is protected from time overruns with buffers. Activity durations are reduced and safety buffers of time are added at the end of the project or sub-network paths. The execution of the project is managed through the use of buffer management. Actually, the core concept of critical chain scheduling is the optimization of work flow through the project.

Location – Based Planning and Controlling System. As previously discussed, construction process modelling, particularly for repetitive projects, needs a more detailed model regarding resource flows through project activities. In Location-Based Management System (LBMS) working tasks, sets of repetitive activities performed by the same resources, are plotted on a time / space chart using general principles of the Line of Balance (LOB) / Flow-line (Kenley, Seppänen, 2010).

The overview of construction control methods from literature, either project-oriented like bar chart, PDM and EVM, or production-oriented like Last Planner, CC and LBMS, actually leads to the need for a major investigation and future research. In fact, the two approaches, traditional and innovative, are really complementary and most of the methods that were presented cover different issues that complete the view of construction from different standpoints. Lean Thinking was really the engine for the development of the new production-oriented control methods. Lean Construction has the goal of giving more value to the final client through improved control in building processes, basically focusing on waste reduction (muda), on making operators more responsible for work assignments, and on the continuous improvement of processes (kaizen). Actually, until planning techniques do not model process flows properly, they will lead to poor planning management or waste improvement. It is concluded that construction control needs the development of an integrated approach that has not been created yet.

3.2 Paper II: Quality Evaluation of Construction Activities for Project Control

This paper is about the search for quality in construction project control, focusing on quality KPIs and the development of a Quality Breakdown Structure (QBS) for the construction project. The paper consists of a literature review to detect the available KPIs for the implementation of a quality related metric and of the proposal of the adoption of the QBS as a basic method for construction project quality control. The solution idea was tested on two case studies of building construction, and one of them was presented in the paper. The qualitative and quantitative research methods are followed in this constructive research effort. The paper contribution is the definition of quality – related KPIs for a construction project for project control purposes. The main task of the research is the definition of the Quality Breakdown Structure as a method of assessing project quality performance through the as – of date for project control purposes.

The measurement of the performance of a construction project is a fundamental task of Construction Management. This is usually based upon professional observations or use of metrics such as Key Performance Indicators (KPIs), which are intended to represent the health of the construction project and can be used to predict future project performance. The relevant problem of the measurement of the quality performance of a construction project was individuated, meaning how the quality of a construction project is delivered and controlled. The quality delivered to the final client is both the technical quality of the final product (the building or the civil engineering infrastructure) and building process quality. The study of previous literature about construction quality estimate and construction project metrics has allowed for the benchmarking and analysis of existing approaches to construction project quality evaluation, highlighting positive and negative issues of each approach. The research has also been based on two actual construction projects that have been described from the quality standpoint in recent studies performed at the University of Bologna, and one of them is presented in the paper.

The research has been developed in three phases. In the first phase, literature about project metrics and construction project performance measurement is reviewed. In particular, existing and proposed project quality KPIs computation methods are focused. Three approaches were selected because of their relevance and their presentation in prestigious international scientific journals. The first approach of the UK's KPIs Working group (Minister of Construction, 2000) defines quality KPIs basically as the frequency of defects in the end product. The aim of the quality KPIs is to improve the visibility of quality issues on construction projects through the measurement of "Quality Issues". The second approach is that of the Construction Industry Development Board of Singapore that developed an objective quality measurement system for building construction called CONQUAS (2008), which is now also used as a quality standard for ISO 9000 local enterprises quality certification. The third approach to quality index evaluation is the one used by El Rayes and Kandil (2005) in recent studies for highway construction, in order to facilitate the measurement and quantification of construction quality.

The paper develops a new quality KPI definition, for a construction project, through the integration of the three approaches previously described. The proposed operational procedure was applied in two cases and in the following, a simple case study of a retrofitting project of two buildings of a public institution is synthesized and presented.

Table 3.1: Case study: reinforced concrete work package quality evaluation (Qi), product and process quality

WORK PACKAGE: Structural work - reinforced concrete

j	Quality index (j)	Weight of index (Bi,j)	Quality Index (Qi,j)	Quality Index weighted (Qwi,j)	Work Package Quality Performance (Qi)
1	Concrete Quality	10	100%	10	
2	Finished Concrete	8	80%	6,4	
3	Rebar	8	95%	7,6	
4	Formwork	7	80%	5,6	
	Total	33		29,6	90%

In the second phase, the activity quality performance quantification problem is tackled. Firstly, it is necessary to specify construction project activities through a Quality Breakdown Structure (QBS) that identifies work packages that group activities with similar quality specifications. Then, the proposed method for quality KPI estimation can be used to evaluate the quality performance of Work Packages related to two groups of requirements: product or sub-product related requirements and process or sub – process related requirements. The KPIs' weighting system is the core process of quality evaluation. The QBS allows one to identify the quality control points of the construction project (Figure3.1).

The paper proposes to evaluate quality of a construction activity through quality indexes for each quality item defined in the Work Package of the QBS that include the activity. The definition of quality items for each WP is developed by means of the ISO 9001 Quality Plan for the specific construction project. Table 3.1 shows the quality items for the example of the reinforced concrete Work Package of the case study. Quality items should be quantifiable or measurable and are related to both product quality and process quality. In Table 3.1 the finished concrete quality item comprises concrete vibration and cast in place.

In the third phase, an overall project quality assessment through the as-of date is performed. This is allowed by quality weighting of the WP of the QBS. The weighting system at the project scale is realised taking into account economic, aesthetic or functional aspects of the specific construction project. Then, by adding the weighted WP performance of each WP accomplished at the as-of date, the quality project status can be evaluated at each time-now or on a real time basis. The Quality KPI, representing the overall quality of the Construction Project, can be estimated as the sum of the quality of each Work Package of the project, weighted to represent the importance and contribution of the quality of every Work Package to the overall quality of the project. Table 3.2 shows relative weights of the activities of the sample project. It should be noted that, by loading quality performance to the project schedule, it is possible to assess quality performance of the construction project through the as-of date. In this way, the reporting system of the project status can also cover quality information. Table 3.2 shows the case study Quality KPI (Q) evaluation at project completion.

PROJECT QUALITY PERFORMANCE	A _i	WORK PACKAGE (I) QUALITY PERFORMANCE	B _{i,j}	WORK PACKAGE QUALITY ITEM (J)
1 HOUSING CONSTRUCTION PROJECT	A1	1.01 BUILDING SITE ORGANISATION	B1,1	1.01.01 BUILDING SITE LAYOUT
			B1,2	1.01.02 FENCE/SIGNALS
			B1,3	1.01.03 ELECTRICAL PLANT
			B1,4	1.01.04 SCAFFOLDS/FALL PR
			B1,5	1.01.05 TOWER CRANE
	A2	1.02 REINFORCED CONCRETE	B2,1	1.02.01 CONCRETE QUALITY
			B2,2	1.02.02 FINISHED CONCRETE
			B2,3	1.02.03 REBAR
			B2,4	1.02.04 FORMWORK
			B3,1	1.03.01 BEAM/WALL JOINT
	A3	1.03 WOODEN FLOOR CONSTRUCTION	B3,2	1.03.02 FLOOR WOODEN STR
			B3,3	1.03.03 WOOD QUALITY
			B4,1	1.04.01 BEAM/WALL JOINT
	A4	1.04 WOODEN ROOF CONSTRUCTION	B4,2	1.04.02 ROOF WOODEN STR
			B4,3	1.04.03 WOOD QUALITY

Figure 3.1: Quality Breakdown Structure of the case study.

Table3.2: Case study: Construction Quality KPI (Q) at project completion.

PROJECT QUALITY KPI (Q)	WP WEIGHT (A _i)	WORK PACKAGE DESCRIPTION	WORK PACKAGE QUALITY PERFORMANCE (Q _i)
	3,0%	BUILDING SITE ORGANISATION	87%
	5,0%	REINFORCED CONCRETE	90%
	5,0%	WOODEN FLOOR CONSTRUCTION	90%
	15,0%	WOODEN ROOF CONSTRUCTION	90%
	2,5%	EXTERNAL WALL	85%
	2,0%	INTERNAL WALL	85%
	3,0%	ROOF COVERING	88%
	4,0%	PLASTER FINISH	90%
	7,0%	FLOORS AND WALLS TILED FINISH	90%
	2,0%	PAINTINGS	93%
	17,0%	PLUMBING AND SANITARY WORK	85%
	10,0%	ELECTRICAL WORKS	92%
	2,0%	THERMAL AND SOUND INSULATION	90%
	3,0%	SITE IMPROVMENTS	88%
	2,0%	DEMOLITION	77%
	17,0%	DOORS AND WINDOWS	94%
	0,5%	EARTHWORKS	90%
89,4%	100,0%		

3.3 Paper III: REPNET: Project Scheduling and Workflow Optimization for Construction Projects

This paper is about the proposition of a process-oriented construction scheduling method, focusing on a heuristic method based upon a Precedence Diagramming network plotted on a resource-space chart. The paper consists of a literature review of a construction – oriented scheduling method and of the proposal of a heuristic procedure, termed REPNET, implemented for a sample building process. The mixed research method and the constructive approach are followed. The paper contribution is the definition of a heuristic procedure to help inexperienced construction project planners in the resource / space constrained scheduling process. Two main tasks are tackled in the paper: the planning and scheduling procedure must be such as to permit inclusion of work-continuity requirements; and the project duration found must be minimized in order to minimize project cost, and overhead cost in particular.

The developed heuristic is based upon a precedence activity network plotted on a resource – space chart, with the aim of improving resource-based scheduling with the Precedence Diagramming Method in construction projects. The proposed heuristic algorithm is termed Repetitive Networking Technique (REPNET), and can develop a schedule model for a construction project composed by repetitive activities performed in different project locations (Bragadin 2010, Bragadin, Kähkönen 2011). The flow-line view of the project is integrated in REPNET.

The REPNET heuristic procedure for resource-based construction process optimization is a semi/automatic procedure that can help inexperienced schedulers in construction project scheduling. The optimization processes carry out resource timing in three phases: resource – space network implementation, schedule optimization with constant resources and final schedule optimization with resource allocation modification.

REPNET Phase I. The Precedence Diagram Network of the repetitive project is plotted on a resource – space chart, with the x-axis representing resources and the y – axis representing space units of the project. Therefore, the network's nodes representing activities are identified by a two-coordinate system: the main resource performing the activity and the workspace in which the activity is to be performed. The procedure of plotting the network on resource – space coordinates has been used by many researchers in the past (Yi, Lee and Choi, 2002). The resource – space chart has been developed further in the REPNET method and coordinated with flowline charts. (fig. 3.2).

REPNET Phase II. After PDM critical path analysis, minimum construction project duration is found and the As Soon As Possible (ASAP) project schedule is created. In general, non-zero link lags due to early time positioning of activities belonging to the same resource path prevent the ASAP schedule from satisfying the work continuity requirement. The proposed method aims at minimizing idle time of crews by activity shifting. Due to this fact, the REPNET optimization algorithm does not modify Total Project Duration (TPD) as computed by traditional forward pass of Precedence Diagramming, and the workflow continuity can be obtained only if made possible by network logic, activity float and feasible resource modification. The resource- space chart enhances Location Based Scheduling. The focus is on the process performed on a sequence of locations by resources. So the flow of resources must be protected with buffers to allow for variability (Kenley and Seppänen, 2009). A buffer is a time allowance provided to absorb any disturbance between two activities or tasks. While the process of scheduling tasks with the work continuity requirement usually causes an increase of the total project duration (Selinger 1980, El Rayes and Moselhi 1998, Vanhoucke 2006), the REPNET procedure prevents this effect by keeping the original CPM Total Project Duration unchanged. Anyway, this process consumes float augmenting the number of critical activities in the schedule, so the lack of robustness of the schedule in terms of capability of absorbing delays must be insured by the insertion of contingency buffers.

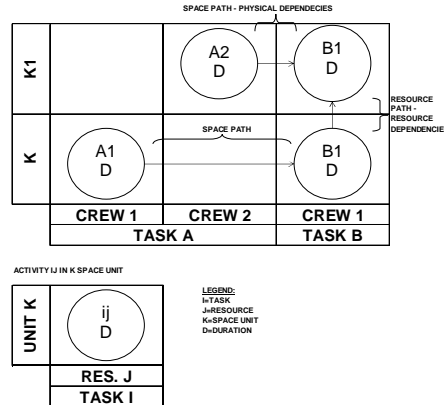


Figure 3.2: Network diagram plotted on a Resource-Space Chart (adapted for Yi, Lee and Choi, 2002).

REPNET Phase III. For a further optimization of the construction process total duration, the flow line view of construction projects is considered. The tasks that proceed faster or slower can be selected by simple observation of the slope of the flow-lines. Faster tasks will have a greater slope than slower ones. Therefore, schedule can be optimized further by changing the production rates so that the slopes of preceding and succeeding tasks are aligned to be as close to parallel as possible (Lowe, D'Onofrio, Fisk, Seppänen, 2012). The alignment optimization can reduce further total project duration, but the duration gain is, instead, used to insert a project buffer to prevent contingency at a project level (Steyn, 2000). The production rate of optimized tasks can be changed by adjusting resource allocation for the specific set of activities. Crews can be increased or decreased until the slope of the task is similar to its predecessor, or until no more resources are available, or the lower threshold limit for activity performance is reached (Kenley, Seppänen, 2010).

The proposed method is implemented for a simple example project. The example concerns a small rehabilitation construction project of a five-storey building. Three tasks are considered: concrete slab pouring (A), plastering (B) and paving (C). These three tasks must be performed by crews in every space unit of the project. The Location Breakdown Structure is very simple, and consists of five space units, which are the five floors of the building. The example project has the following assumptions: only one crew for concrete slab pouring (A1) and for paving (C1), two crews for plastering (B1 and B2). The working hypothesis is that work assignment is a constant of the project and so labour – days for each activity performed in a single space unit are fixed. Activity duration computation can be found simply by division of labour days with the number of crew labourers.

REPNET is then performed (figures 3.3.a) - b) and 3.4). The ASAP scheduling can be found in figure no. 3.3.a), while the REPNET final network is presented in figure 3.3.b) and the corresponding flow line in figure 3.4. It should be noted that the complete optimization of all the project resource paths has been achieved.

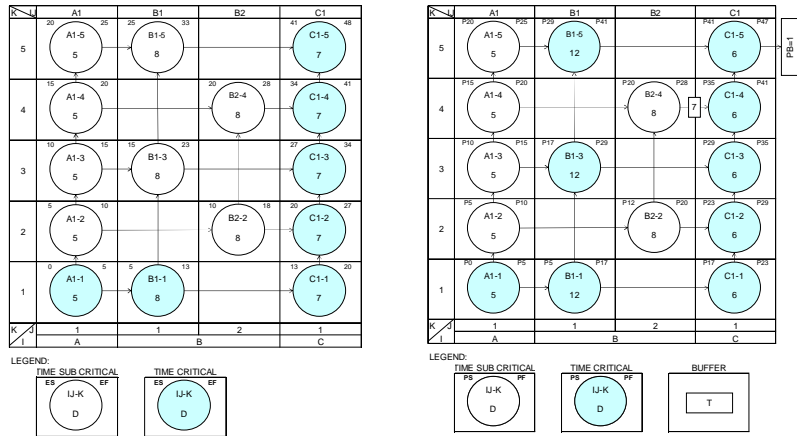


Figure 3.3: REPNET a) phase 1 ASAP Schedule; b) phase 3 optimized schedule.

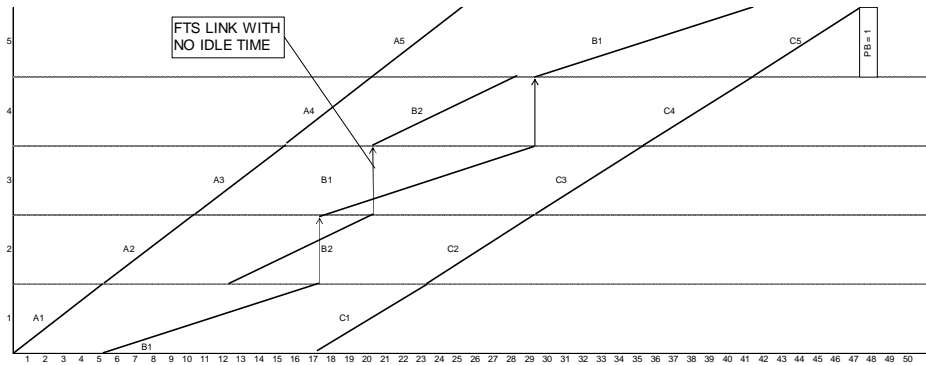


Figure 3.4: REPNET: flowline of phase 3 – project workflow optimised.

Some critical points of traditional Network Scheduling for construction projects are tackled by implementing workflow optimization through Location Based-Scheduling and flow-line graphs. In particular, the resource-driven scheduling is implemented by network plotting on the resource – space chart, where, for each activity, resources and location are set in one time. These features of the schedule model make the implementation of resource - flow tracking possible, i.e. the view of the planner of the movement of resources through the locations of the construction project. Also, the flow-line view highlights the workflow, the production rate and the use of resources (e.g. crews and equipment) on the same graph, thus providing an easy-to-control schedule, improving the control phase during project execution.

3.4 Paper IV: Schedule Health Assessment for Construction Projects

This paper is about the problem of understanding the quality of a construction project schedule, focusing on the needed quality requirements. The paper consists of a literature review of the quality requirements needed for a construction schedule and of a proposal of a procedure to perform quality control of a construction schedule in the design and maintenance phase, termed "Schedule Health Assessment". The mixed research method and the constructive approach are followed. The paper contribution is a method performing the assessment of the quality of the schedule of a construction project, and the definition of the characteristics that a good quality schedule should have. This can be defined as "Schedule Health Assessment". This procedure can also be used as guidance in the development of the schedule by project schedulers.

Little research has been found to be directly related to quality of schedules, and most of it is not construction oriented. Although, a set of quality requirements applicable to a construction schedule have been defined by a literature review and also by experience from practical implementation. The defined set of quality requirements indicates a metric to measure schedule quality. The schedule requirements have been classified and weighted related to their importance and a method of schedule health assessment has been developed. The method can help project planners to produce a good quality schedule since the initiation of the project and, during the execution phase, it can be used to perform a schedule health assessment to detect deficiencies and issues to be addressed for construction control purposes.

Basically, schedule quality is the result of the interaction between two main components, construction knowledge transferred into project schedule and schedule mechanics knowledge. Construction knowledge means the set of information related to construction technology implementation in the building construction process, while schedule mechanics knowledge means the set of information related to scheduling technology, i.e. scheduling and activity network rules. Though in most standards, recommended practices and pertinent literature for construction schedules these two different bodies of knowledge are addressed with quite separate approaches, an integrated approach is proposed to improve quality. Therefore, Schedule Health Assessment Indicators are developed to address both of these two bodies of knowledge used for construction scheduling.

Firstly, schedule quality requirements available in the literature, as defined by researchers, by international standards and by recommended practices, have been identified. More than one hundred specific schedule quality requirements have been evaluated and classified. Secondly, a selected group of seventy-five requirements has been identified and classified in five groups of requirements. These five groups of requirements are termed Schedule Health Indicators. Each schedule indicator aims at defining a quality level of schedule performance in a specific topic to assess schedule health. The five schedule health indicators are the following:

1. General requirements
2. Construction process requirements
3. Schedule mechanics requirements
4. Cost and resources requirements
5. Control process requirements

Each indicator is, in turn, composed of a number of requirements aimed at developing a construction project schedule of a good quality level. The five schedule health indicators do not have the same importance in the planning and scheduling process. While some of the studies and recommended practices focus on the

requirements related to constructability (De la Garza, 1990; Dzeng, Lee 1999; Douglas, 2009), which mainly corresponds to the Schedule Health indicator no. 2 (Construction process requirements), most of guidelines and standards, (PMI, 2007; U.S. DICMA, 2012; PMSC - NDIA, 2012) highlight the importance of the scheduling process and of the scheduling product quality. This body of knowledge includes scheduling process and schedule mechanics, which are related to Schedule Health indicators no. 1 and no. 3, (General requirements and Schedule mechanics requirements). Moreover, Moosavi and Mosehli (2012), who performed a survey based on feedback from professionals in the construction industry, indicate as top schedule assessment criteria those related to the scheduling process and to schedule mechanics. Concerning cost and resource loading requirements, though they are fundamental players in the planning and controlling processes, together with control requirements, it seems that the other indicators are more noteworthy for effective scheduling. Therefore, since the number of detailed requirements from pertinent literature of each Schedule Health Indicator seems to be directly related to the level of importance of each indicator, the developed method weights each Indicator in function of the number of the composing detailed requirements.

The schedule health assessment procedure can be accomplished in a straight forward manner. Each Schedule Health Indicator (i.e. General requirement) is composed by requirements (i.e. Schedule process procedure, schedule definition, activity definition). Seventy-five requirements were selected from literature and standards, thus enabling an in-depth evaluation of a construction schedule. Each requirement, in turn, is made up of various detailed requirements. Firstly, the detailed requirement list is evaluated. The scheduler checks if each detailed requirement is satisfied by the project schedule. For each satisfied detailed requirement by the project schedule, a point is earned. Then the value of each Schedule Indicator is found. The weighted sum of each indicator is the Schedule Health Assessment ranking, termed SH.

A sample application has been developed, regarding a simple detailed schedule of an actual construction project of a small sports facility located in northern Italy. The scheduling software used is the MS Project®. The network is composed of 179 activities. A fragment of the sample schedule can be found in fig. 3.5. The Schedule Health Assessment procedure was performed with the help of a checklist, and the final grade SH achieved by the schedule was found. The estimated SH value was 77%. The table 3.3 shows the report sheet of the Schedule Health Assessment method, developed for the sample project.

Quality assessment of a construction project schedule is a challenging task. The paper defines a metric to measure the Schedule Health Assessment of a construction projects. The method identifies five Schedule Health Indicators. The weighted sum of the performance level of each indicator for the construction schedule under evaluation is defined as the Schedule Health Assessment. The method has the aim of being a proactive quality control approach for detailed construction scheduling. Though the Schedule Health Assessment was developed for the project team of the construction company, it can also be used by the owner's consultant to evaluate the contractor's detailed schedule.

Schedule Health Assessment procedure was tested in a case study of a construction project schedule. The method was able to highlight critical elements and strength features of the construction schedule, performing a simple but accurate analysis. Future research will aim at method development and at empirical data testing with the proposed method.

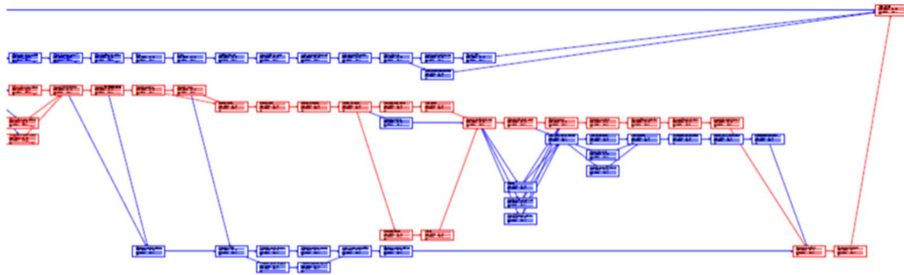


Figure 3.5: Fragnet of the case study schedule.

Table3.3: Schedule Health Assessment of the case study. Report sheet.

No. Req.	Requirement description	Req. score	Indicator score	Wq	Si	Swi
1)	General requirements (17):		13	23%	76%	18%
a.	Schedule process procedure (4);	1				
b.	Schedule definition (5);	5				
c.	Activity definition (8);	7				
2)	Construction process requirements (11):		10	15%	91%	14%
a.	Activity sequencing (3);	3				
b.	Activity duration (3);	3				
c.	Activity timing (2);	2				
d.	Construction process productivity (3)	2				
3)	Schedule mechanics requirements (27):		26	36%	96%	35%
a.	Network and logic (6);	6				
b.	Critical path (9);	9				
c.	Float (4);	4				
d.	Soft & hard Constraints, buffers (4);	3				
e.	Activity mis-assignments (2);	2				
f.	Lag & lead (negative lag) (2);	2				
4)	Cost and resources requirements (9):		0	12%	0%	0%
a.	Monetary value/cost of activities (3);	0				
b.	Project cost ratio (1);	0				
c.	Resource loaded activities (3);	0				
d.	Project total level of effort (2)	0				
5)	Control process requirements (11):		9	14%	82%	11%
a.	Activity progress evaluation (2);	2				
b.	Schedule review and baseline (4);	2				
c.	Schedule projections (2);	2				
d.	Invalid dates and missed tasks (3).	3				
SH =						77%

3.5 Paper V: Safety, Space and Structure Quality Requirements in Construction Scheduling

This paper is about construction process related requirements for the definition of the quality of a construction project schedule, focusing on the 3 “S” rule, meaning “Safety, Space and Structure”. The paper consists of a proof of concept and a research feedback of the proposed Schedule Health Assessment method. The mixed research method and the constructive approach are followed. The paper contribution is the assessment of construction schedule quality by defining construction process-oriented quality requirements. The study starts by defining time-space conflicts and, through detailed analysis of a sample case study project schedule, seeks to supply evidence of the importance of the 3“S” rule in scheduling quality. The 3“S” requirements are then integrated into a more general Schedule Health Assessment Method. Sample project data are derived from a simple case-study of an existing building refurbishment project

The paper is a connecting paper that aims at focusing the developed schedule quality assessment method (in paper IV) on the construction process safety problem. The aim is to validate the proposed Schedule Health Assessment method with the “3S” rule for construction scheduling meaning “Safety, Space and Structure”. In a previous paper (paper IV), a set of seventy-five schedule quality requirements has been defined and a construction schedule quality assessment procedure was developed. This includes the classification of schedule requirements into five groups termed as Schedule Health Indicators: general requirements, construction process, schedule mechanics, cost and resources, and control process. Although five Health Indicators have been individuated, it is thought that construction process requirements play a major role in the quality assessment procedure.

Concerning sound preparation of a project schedule from the viewpoint of the construction process, a well-known rule-of-thumb for construction scheduling is the 3 “S” rule. The 3 “S” are Safety, Space and Structure, meaning that the planned process should provide a safe working environment to construction workers, sufficient space to perform construction activities and the required sequence of construction operations and project phases. These requirements are of capital importance for schedule effectiveness.

The paper has the aim of developing a Schedule Health Assessment Method that takes into account the 3“S” rule of the construction process, and its content is limited to the proper implementation of this rule into the scheduling development process. Another sub-aim of the paper is to integrate the 3“S” rule – related requirements into the framework of the five Schedule Health Assessment indicators previously defined. The paper first analyses the schedule quality problem, as approached by pertinent literature and standards, then the 3“S” rule for construction scheduling is examined in relation to the work of Callahan, Quackenbush and Rowings (1992) that first defined the 3“S” rule scheduling approach. It also addresses the seminal works of Kenley and Seppänen (2010) about Location-Based Management System for construction and of Akinci, Fisher, Levitt and Carlson (2002), who investigated time-space conflicts in construction projects.

The 3 “S” rule for construction scheduling, meaning “Safety, Space and Structure”, is taken as a fundamental rule to synthesise quality requirements of the construction process. Process design through schedule model implementation must satisfy the 3 “S” rule to obtain a good quality schedule. In addition to this, a location – based system is believed to be the answer to the need of creating a construction-oriented scheduling approach. While the “Structure” rule for network logic creation is really about the proper setting of dependencies between project activities, the “Safety” and the “Space” rules are really about time – space conflicts. The “Space” rule is concerned with space requirements for: crew (i.e. working space), equipment and temporary structure. Mainly, it prevents simultaneous use of the same space by different crews/activities. The “Safety” rule requires the project scheduler to check safety problems due to errors in the activity sequence that can affect the safety of construction workers, and hazards created by working tasks in other space units.

All these issues can be addressed by Location-Based Planning (Kenley and Seppänen, 2010). In fact, Location – Based management assumes that there is value in breaking a project down into smaller locations and using these to plan, analyse and control work as it flows through these locations. The location provides a container for project data at a scale that is easy to schedule and to control. The emphasis in location – based scheduling is to schedule the construction project, achieving high level of productivity, quality and safety. Once the project is broken down into various locations, or space units, it is necessary to understand the interactions between activities and spaces. The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six types of spaces required by construction activities were detected:

1. Building component space
2. Labour crew space
3. Equipment space
4. Hazard space
5. Protected space
6. Temporary structure space

Each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur.

A sample application of the 3 “S” rule to a typical construction schedule of a small refurbishment project is used to illustrate the problem. The activities of the energy retrofitting project of a residential four – storey building are: scaffolding, roof retrofitting, external wall insulation, base coat and wall finish, windows retrofit. The first version of the construction schedule has some time - space conflicts and hazard spaces because of the time overlapping of “D - base coat” and “E - windows retrofit” activities with “C - external wall insulation”, but has a very short total duration (fig. 3.6 a), 3.6 b)). The improved schedule, developed by applying the test of the 3 “S” rule, is very different (fig. 3.7 and 3.8). The time – space conflicts of activities have been resolved, as the corrective action eliminated the hazard space created by the preceding activities in conflict with the succeeding ones, but the total duration has increased. It is clear that only the integration between the two scheduling tools, the CPM network and the flow line chart, can explain clearly the interactions between activities and space, thus highlighting possible time-space conflicts.

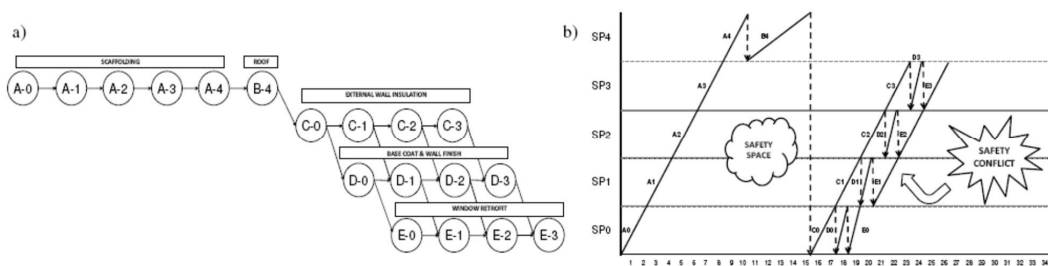


Figure 3.6: Sample project schedule before 3 “S” analysis: a) CPM schedule; b) Flowline schedule.

As a result, the 3 “S” rule-of-thumb can fit very well with a Schedule Health Assessment procedure, as it highlights construction process requirements of the schedule. In particular, a specific “Construction process safety and productivity” requirement can be implemented in the assessment procedure, though this requires, to be more efficient, the development of a flow-line chart of the schedule. Limitations of the research work are related to the simple example used as a case study. It is felt that future testing on several construction project case studies has to be performed to fully develop a complete testing and commissioning of the Schedule Health Assessment method integrated with the 3 “S” rule.

The paper highlights the need of flow-line view of the construction schedule to be really process-oriented. Flow – line view has become an irreplaceable tool for schedule health assessment, as the integration of the networking technique with the flow line chart highlights possible time-space conflicts. In fact, the 3“S” rule is mostly oriented toward space usage in the building process, and this enhances the need for a space – oriented scheduling tool. Thus, the flow-line view of the activity network becomes another quality requirement of the construction project schedule.

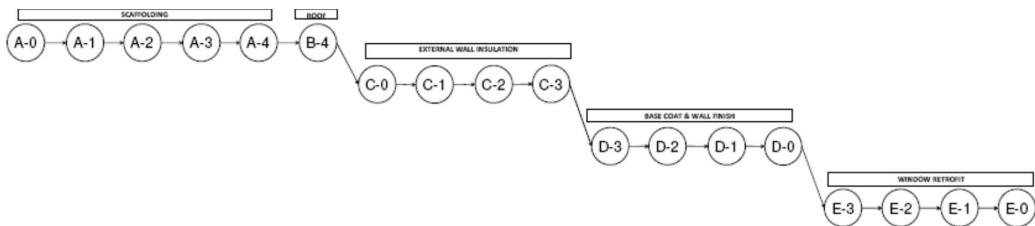


Figure 3.7: Sample project schedule after 3 “S” analysis and correction: CPM schedule

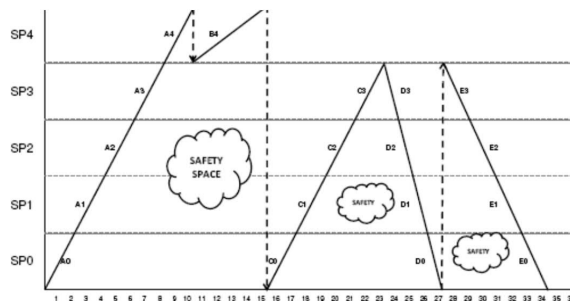


Fig. 3 . Sample project after 3 “S” analysis and correction: Flow Line schedule

Figure 3.8: Sample project schedule after 3 “S” analysis and correction: flowline schedule

3.6 Paper VI: Resource – Space Charts for Construction Work Space Scheduling

This paper is about the proposition of a method to understand work-space characteristics of a construction project for planning and scheduling purposes, thus creating a process-oriented environment for construction schedule production, and enabling high quality scheduling. The paper focuses the use of the Location Breakdown Structure and of resource – space charts for construction scheduling. The paper consists of a literature review of process-oriented scheduling methods for construction projects, and of the proposal of a complete planning, scheduling and controlling method, the REPNET, based upon a PDM network plotted on a resource – space chart for workspace scheduling. The mixed research method and the constructive approach are followed. The paper contribution is the development of a workspace management method based upon resource-space charts and Location Breakdown Structure (LBS) for activity network plotting. The LBS allows loading a maximum number of resources (crew) into each space unit, thus defining the available space capacity of working crews. In this way, the project scheduler can verify the quality of the produced schedule during the planning and scheduling process, as dimensions of workspaces and their congestion limits, safety spaces and protection spaces can be easily verified. A resource-space control chart can be plotted for each week to facilitate the monitoring of the project status. The method has been tested on a case study.

The space identification for a construction schedule can be addressed by Location-Based Planning (Kenley and Seppänen, 2010). The Location Breakdown Structure (LBS) is the backbone of this design process for on-site operations. Once the project is broken down into various locations, or space units, one must understand the interactions between activities and spaces. In this phase, the required spaces for each activity are detected and assigned to space units. Repetitive activities are then broken down into various activities to be performed in specific space units due to their production features, and single activities are allocated to specific spaces of the LBS. The sequence of activities is then generated using Precedence Diagramming Method (PDM). Activities are sequenced with network logic links, and consecutive and concurrent work tasks are defined first for each space unit and then for the complete building project. The prepared activity network can now be plotted in the resource - space chart. The allocation of activity in the resource – space chart can highlight possible time/space conflicts between activities, and the flow-line view of the schedule model highlights possible conflicts. Conflict resolution can be performed, and the optimized space-allocated schedule can be completed. The flow-chart of the proposed scheduling process can be found in figure 3.9.

The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated time-space conflicts in construction projects. Six types of spaces required by construction activities were detected: building component space; labor crew space; equipment space; hazard space; protected space; temporary structure space. Each construction activity requires at least one of these spaces. In the proposed method, four types of conflicts are identified for project scheduling purposes:

- Time / space conflicts due to activities time-space overlapping and consequent contemporary space usage
- Congestion of space due to labour density
- Safety hazards due to hazard spaces created by an activity
- Damage conflicts due to spaces required by an activity conflict with a protected space of another activity

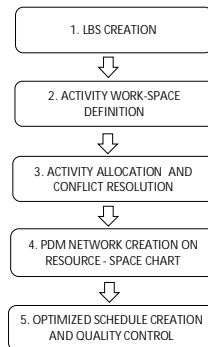


Figure 3.9: Proposed scheduling process

The proposed resource – space chart based method can help a project planner and production managers avoid conflicts in many ways. In fact, time-space conflicts can be avoided due to space allocation of activities in the resource-space chart. At the same time, the layout space for each activity execution is identified on the chart, and it is easy to indicate the maximum number of workers per space unit. Safety hazard spaces and protected spaces can be represented as unavailable spaces for a specific time window. The basic limit of the proposed solution is the level of detail of the LBS, and the consequent representation of space conflicts between activities.

A sample construction project of a small three storey residential building is presented. The case study focuses on the workflow model created for the construction phase of the systems and interior finishing works. After the LBS creation, work spaces of each activity have been defined and the maximum number of workers per space unit can be assigned. Labour density limits are set with the aim of satisfying technology and safety requirements. In figure 3.10 the maximum number of workers per space unit is shown.

The creation of PDM network on the basis of the Resource – Space chart (fig. 3.11) is then easy to develop as a following step, since it is only necessary to add logic links on the previous pattern of activity allocation on the LBS (fig. 3.10). The REPNET heuristics (see paper III) is then performed and a workflow optimized schedule is developed. In figure 3.12, the flow-line chart of the sample project is depicted. For each working week, the state of the project can be plotted, thus facilitating the controlling process through the building site as the controlling chart shows completed and in-progress activities with successor spaces. Unavailable spaces, e.g. because of cement screed hardening after cast in place of cement itself (activity D), are highlighted with a different color in the chart to ease production management of succeeding construction processes (fig. 3.13).

Linking the proposed workspace scheduling method with BIM models capturing location details of the end product is an interesting way to develop the proposed method further. This would mean directly capturing the location data of interest from the BIM model to be used for scheduling purposes. Detailed BIM models can be very effective for workspace conflict detection (Akinci et alii, 2002; Choi et alii, 2014; Ciribini, Galimberti, 2005; Dawood, Mallasi, 2006; Mallasi 2006; Zhang et alii, 2015), but it is also believed that a simple space modelling approach, like the one presented and based on the LBS development, can be a quick and efficient method for workspace scheduling (Kenley, Seppänen, 2009, 2010; Russell, Tran, Staub-French, 2014).

3.7 Paper VII: A Planning and Scheduling Paradigm for Construction Strategy of a Building Rehabilitation Project

This paper is about the proposition of a resource-based paradigm for construction project detailed planning, focusing on defining construction strategy as performed by the contractor's production managers. The paper consists of a literature review of the concept of strategy in construction projects and its possible implementation through project scheduling in a case study of a building rehabilitation project. The mixed research method and the constructive approach are followed. The paper contribution is the analysis of the several alternatives of project strategy found in the owner's initial project schedule for the bidding phase, and possible alternatives in the contractor's detailed schedule. The proposed approach for project strategy definition is based on the development of construction-oriented project schedules, created with activity network plotting on resource-space charts. With this method, two different alternatives of project strategy are developed for the case study.

Strategic decisions for a construction project play a fundamental role in the search for project success. The use of a process-based paradigm for planning and scheduling can help construction managers to create different production scenarios, to choose the more suitable strategy for the building construction project. In rehabilitation construction projects, multiple project work scenarios are possible because of the existing building structure that creates different work areas. Rehabilitation construction projects have, indeed, some specific features. First of all, the existing building creates a spatial constraint for building activities in terms of accessibility and layout of working placement, i.e. space for construction operations, and in terms of transportation of building materials and transportation and use of machines and equipment. On the other hand, the possibility of contemporary or overlapping construction operations, because of the structure of the locations of the building, can give flexibility to the planning of activities, i.e. different alternatives for the sequence of the operations.

The proposed resource-based method for project scheduling is proposed for the construction strategy definition as can be performed by the contractor's production / construction managers. In fact, construction project managers need to realistically simulate the construction process to create different scenarios defined by different strategies, with the aim of construction optimization as to reach project objectives. This task can be accomplished through the proposed planning and scheduling paradigm termed Repetitive Networking Technique (REPNET), based upon a Location Breakdown Structure (LBS), a Precedence Diagramming network plotted on a resource – space chart and flow-lines (paper III and VI).

The Project Strategy is a comprehensive definition of how a project will be developed and managed (APM, 2006). Artto, Kujala, Dietrich and Martinsuo (2008) define Project Strategy as the direction in a project that contributes to the success of the project in its environment. Strategy is not a plan (Patanakul, Shenhar, 2012). Russell et al. (2014) gives the following notion of construction strategy: "a strategy for constructing a spatial / system element of a project consists of an approach comprised of a strategy mode and the means for achieving it in the form of specific tactical variables and accompanying values, selected in response to client or contractor objectives and project constraints and conditions, as of a specific point in time". There are the fundamental strategy modes: normal duration delivery, accelerated delivery and phased delivery.

Therefore, project strategy can be mainly developed through the project schedule. In the Italian construction sector, the general approach to project scheduling is defined by Public Works laws and regulations. Therefore, the development of a project schedule is achieved through three different levels of detail. First, the owner's consultant, designer or project manager, creates a project plan which has the specific task of computing the total project duration for contract purposes, the master schedule. Second, the owner's safety consultant ("Safety Coordinator") develops the safety-oriented construction schedule. Then, the general contractor develops the detailed schedule ("Programma Esecutivo Dettagliato"), and submits it

to the owner's works supervisor ("Direttore dei Lavori") for schedule approval before the commencement of works on-site. It is evident that these three different levels of planning and scheduling entail different project strategies on the owner's side or on the contractor's side.

A case study of an existing building rehabilitation project has been used to compare the project schedule prepared by the owner for the bid phase and the different scenarios created by the company for the construction phase with the REPNET. An excerpt of the owner's schedule can be found in figure 3.14. For the sake of simplicity, only the demolition and structural reinforcement phases are presented in the bar chart schedule, developed with MS Project®. Project activities are planned in a sequence regardless of actual work areas, with few overlapping activities. The project strategy mode is "phased delivery" with normal duration, since one single crew can perform most of the activities. The contractor can plan and schedule different scenarios, coinciding with different approaches to project execution. The chosen project strategy mode of the contractor's schedule is "accelerated delivery". The first step is the definition of a Location Breakdown Structure. The second step is the study of the acceleration of the project through multiple crews loading on activities. Therefore, it is possible to overlap activities because of the different work areas created by different floors and space units of the building. Work safety requirements can be satisfied because the different work areas of activities create no safety work-space conflicts and congestion. In the case study, two project strategies are suggested. Basically, they optimize the workflow sequence through building spaces with multiple crews loading. Four crews are loaded on project phase and each one performs three repetitive activities. The activity durations of the original schedule were kept as constants.

In the first scenario (1), resource paths start from the first floor of the building (figures3.15-3.16). This strategy develops a total duration of the two phases of 106 days versus the 205 days of the original schedule (figure 3.14). In the second scenario (2), the commencement of activities is located on the ground floor, and the two phases can even be completed in 89 days. It should be noted that project acceleration is achieved through multiple-crew loading on activities performed in different work areas.

The REPNET approach seems to be suitable to create a schedule model for rehabilitation construction projects, as they usually have a repetitive "nature", meaning that they have multiple space units where crews perform multiple activities of production of the same construction item. The development of different scenarios for project strategy can be made easily with the proposed method, therefore aiming to create a good quality construction detailed schedule.

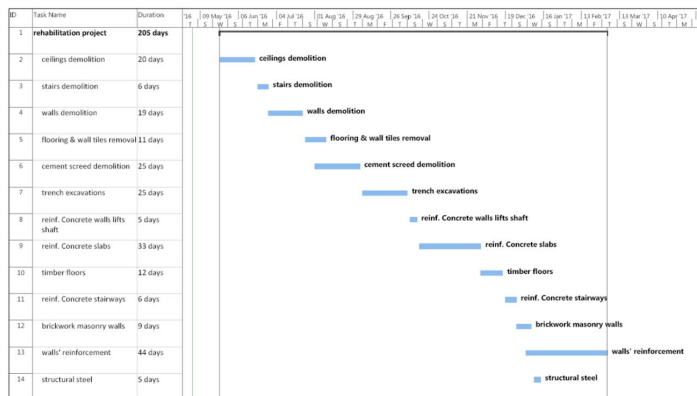


Figure 3.14: Original schedule, demolition and structural reinforcement phase (MS Project®).

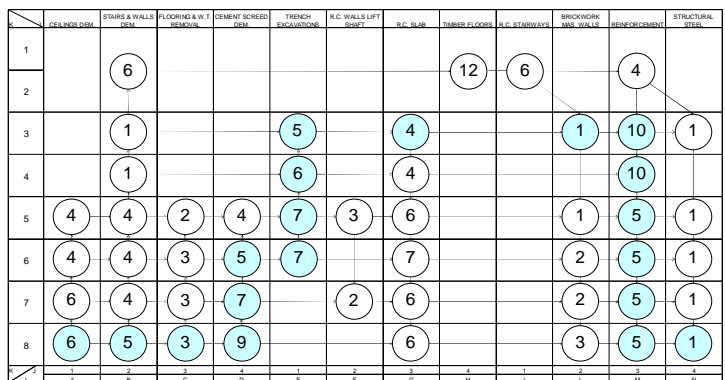


Fig. 3.15: Resource – Space Chart of the case study scenario 1

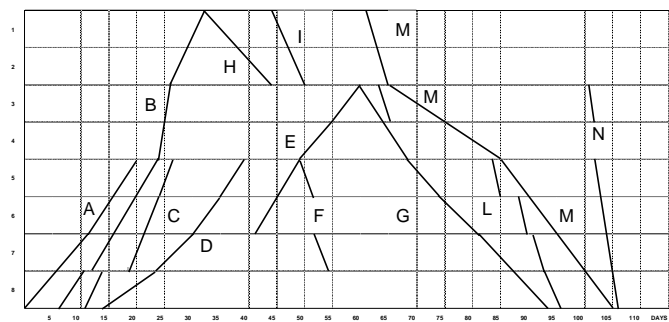


Fig. 3.16: Flow-line of the case study scenario 1

3.8 Paper VIII: Schedule Health Assessment of Construction Projects

This paper is about the problem of understanding quality of a construction project schedule, focusing on the development of a method useful for implementing and assessing the quality of a schedule. The paper consists of a literature review of the quality requirements needed for a construction schedule and of a proposal of a procedure to assess, and create, quality in a construction schedule in the design and maintenance phase, termed "Schedule Health Assessment". The mixed research method and the constructive approach are followed. The paper contribution is the selection of seventy-five quality requirements (out of a set of one- hundred and fifty-six) needed to assess the quality of a construction schedule, and the development of a method of performing the quality assessment, termed "Schedule Health Assessment". This procedure can also be useful as a guide in the development of a quality schedule by project schedulers.

The paper indicates that a method for schedule quality assessment, or schedule quality evaluation, can be beneficial for guiding the scheduling process. The leading idea is to create a proactive method of developing and checking the produced schedule. With this goal in mind, a set of quality requirements applicable to construction schedules has been identified through pertinent literature and by exploring existing standards, and a metric to measure schedule quality is proposed for this purpose. The measurement system is based upon five KPIs, termed Schedule Health Indicators, derived from a categorization of the selected schedule requirements.

The seminal work of De La Garza (1990) and the consequent research and standardization efforts indicated the way forward for a construction schedule quality assessment. From this starting point, and passing through the definition of Project Management and Planning Maturity Model (Zwikaël and Globerson, 2004), a research line has been traced. Various research works initiated this trajectory, citing all the previous works of Birrel (1980) and Laufer and Tucker (1987), which aim both at creating the conditions for producing a good construction schedule, thought of as a symbolic tool of the planning effort of the project management team. The Schedule Management Maturity Model of APM (2012) is a step forward in this direction. The main idea is not only to measure schedule adequacy, but also to indicate the processes, the phases and the working environment needed to create a robust schedule. With this perspective, a method for construction quality assessment has been developed, with the aim of also being a guide for project schedulers in the scheduling process.

The structure of the proposed method is based on five Health Assessment Indicators of schedule quality. These indicators have the task of measuring the performance of the scheduling process and of the produced schedules. Each indicator is composed by different classes of requirements, simply termed requirements are in turn made up of detailed requirements, and these are the "measurement items" of the method. The method originates from a literature analysis in which 156 different detailed quality requirements for scheduling have been identified. These detailed requirements have been used as background data, and they have been classified, analyzed and grouped depending on their specific subject, content and purpose. Finally, 75 detailed requirements have been selected.

The five identified Schedule Health Indicators are the following (fig. 3.17):

1. General requirements
2. Construction process requirements
3. Schedule mechanics requirements
4. Cost and resources requirements

5. Control process requirements

With this information, the quality level indicated by each Indicator can be assessed and a comprehensive quality level, the Schedule Health Assessment, can be evaluated through a weighting process (figures 3.17 and 3.18).

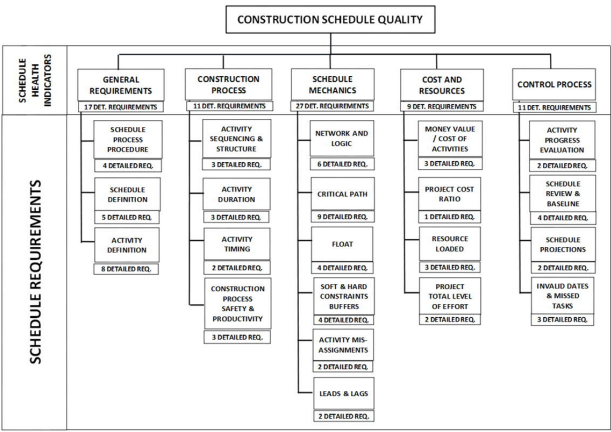


Fig. 3.17: Schedule Health Indicators and Schedule Requirements

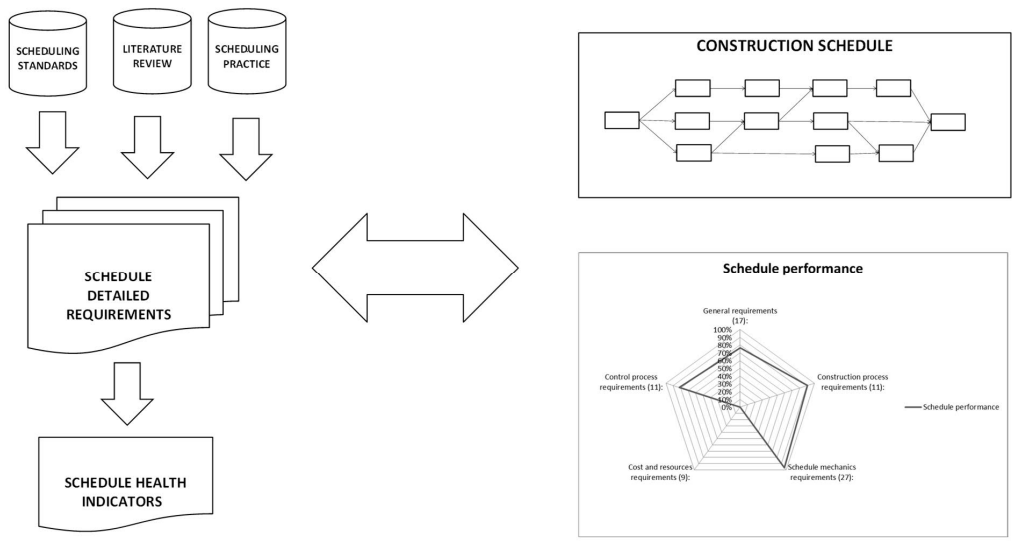


Fig. 3.18: Proposed method framework: Schedule Requirements vs Schedule Performance

The overall Schedule Health (SH) can be quantified with a percentage grade. For each Schedule Health Indicator (Si) the weight (Wgi) indicates the relative importance of each indicator to the others being used to measure the overall performance of the schedule of the construction project.

The Schedule Health Assessment proposed method also has the goal of supporting project planners in the development of a high quality project schedule. With this goal in mind, Schedule Health Indicators have been put in a sequence thinking of their progressive implementation during the planning, scheduling and controlling process. The construction schedule development process can be implemented in three steps: master schedule, detailed schedule, schedule maintenance. The first and the second step form the planning phase, while the third step is related to the control phase.

Practical testing of the proposed method has been carried out in an actual case study, covering both the detailed planning and the controlling phases. A simple detailed schedule of a construction project of a shopping centre has been tested. The original construction schedule was developed with MS Project®, based on an activity network composed of 148 activities. Firstly, the construction detailed schedule was evaluated, and the encompassed Indicators were "General Requirements", "Construction Process", "Schedule Mechanics" and "Cost and Resources". In the execution phase, the Health Assessment procedure was performed for the control phase and schedule maintenance, thus involving all five indicators. In the planning phase, the applied weights (W_{gdi}) for the detailed schedule have been computed in a set of only 64 requirements, and the final grade SH of 67% was found. In the controlling phase, the Schedule Health Assessment procedure was developed with the complete check list of the 75 requirements for schedule maintenance, and the SH value found was 68%.

The Schedule Health Assessment procedure has been developed to perform the quality assessment of the construction schedule. A project schedule has a crucial importance as for project management and thus its planning outputs are to be properly developed and maintained. Poor implementation of the schedule in the construction sector is very common, especially in medium – small size projects. More than this, shortage and limits of network – based programming techniques for construction projects are very well known (Kenley, Seppänen, 2010). Therefore, improved understanding of the quality of construction project time management processes and relating solutions constitutes an important component of project management research.

4. Discussions

4.1 Discussion of the contributions of the research

In its entirety, this dissertation contributes to the body of knowledge of construction project management by studying the role of quality in project planning, scheduling and controlling, and proposing a construction oriented approach for project scheduling and schedule quality identification. The aim of the research work is to understand construction schedule quality, and beyond that, the goal of the research is to highlight the role of project planning, scheduling and controlling as the main project management process. More specifically, this dissertation addresses project schedule model creation as a main component of the project management processes, proposing methods aimed at quality driven scheduling delivering..

Mainly, the dissertation builds on the construction-based scheduling process of Kenley and Seppänen (2010), the Location Based Management System, and on all the previous work concerning schedule quality and construction-oriented scheduling. The dissertation supports the view that construction projects have specific needs in terms of project scheduling (Selinger, 1980; Birrell, 1980; Russell, 1993). Another main source of inspiration was the seminal work of De La Garza (De La Garza, 1990, De La Garza, East and Yau, 1990) aimed at understanding of how owners and contractors evaluate the quality of a construction schedule. The results of this dissertation highlight the role of project planning, scheduling and controlling as the main project management process, and advances construction management research in three ways. Firstly, it suggests that the project schedule should fulfil specific quality requirements, mainly process oriented, with the idea that a set of quality requirements based only upon schedule mechanics or schedule model features (i.e. DCMA 14 points, DCMA 2012) is not suitable for a quality assessment of a construction project. Therefore, the importance of a production-oriented scheduling is highlighted. A new approach for schedule creation and schedule quality control is proposed and tested, termed "Schedule Health Assessment". Secondly, a process – oriented construction scheduling method termed REPNET, based on a network plotted upon a resource – space chart, is proposed and tested on case studies as a quality approach to construction scheduling. But quality should be delivered and usually quality control is not integrated with the traditional time-cost project control approach, although is a main component of project management processes (Atkinson, 1999). Therefore, the use of quality KPIs and of the Quality Breakdown Structure is proposed for the quality control of construction project deliverables. In summary, a quality driven scheduling approach to the construction process is proposed (figure 4.1)..

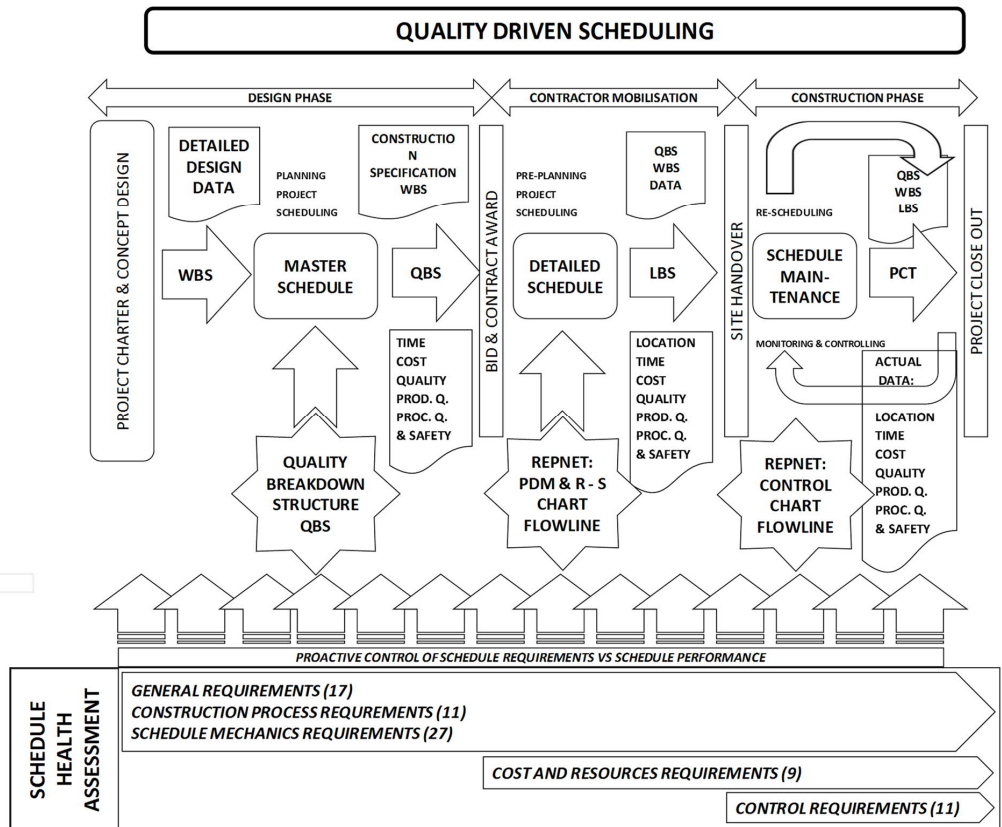


Fig. 4.1: Quality driven scheduling proposed approach

This dissertation contributes to the body of knowledge on project planning, scheduling and controlling, particularly focusing project time management, schedule management and quality management of construction projects. The discussion of the contributions of this dissertation can be performed analysing the contributions of the papers and then focusing core components of the answers to research questions. The research questions are the following.

- Research Question RQ # 1: what is schedule quality?
- Research Question RQ # 2: what is scheduling producing in terms of quality?
- Research Question RQ # 3: can the activity network schedule model be process-oriented and quality driven?

In summary, the answers to the research questions of the dissertation propose a quality driven scheduling process that has the following characteristics:

- i) Proven and reliable scheduling process;
- ii) Schedules meet their different quality criteria;

- iii) Reliable construction process;
- iv) End products meet all project objectives

Each one of the appended papers delivers direct or indirect contributions to this aim, as portrayed in the following table 4.1. The following subchapter discusses the specific contributions of the research.

Table 4.1 Paper direct and indirect contribution to research work.

Research and its results	Summary of contributions	Value of contributions			
		i)	ii)	iii)	iv)
Paper 1	Project Control Processes vs Production Control: Project and process control data and KPIs				
Paper 2	Quality Breakdown Structure, quality KPIs definition				
Paper 3	REPNET method: resource-space chart, flow-line and schedule optimisation algorithm				
Paper 4	Schedule Health Assessment proposal				
Paper 5	Schedule Health Assessment: safety and construction requirements				
Paper 6	REPNET method: workspace scheduling and control				
Paper 7	REPNET method: construction strategy and simulation of process scenarios				
Paper 8	Schedule Health Assessment complete version				

Quality Driven Scheduling

- i) Proven and reliable scheduling processes
- ii) Schedules meet their different quality criteria
- iii) Reliable construction processes
- iv) End products meet all project objectives

Legend:

Characteristics of QDS

i) proven and reliable scheduling process

ii) schedules meet their different quality criteria

iii) reliable construction process

iv) end products meet all project objectives

Value of contributions

Direct contribution towards certain characteristic

Indirect contribution towards certain characteristic

4.2 Improved understanding of the schedule quality (RQ #1)

Answers to RQ #1 produced a method of understanding and measuring schedule quality in construction projects. In particular, Papers IV and VIII describe a method useful to developing and assessing the quality of project schedules for construction. The method is based upon 75 detailed requirements grouped into five Schedule Health Indicators. The detailed requirements were individuated through analysis and evaluation of 156 detailed requirements found in existing literature and standards. No broader study about schedule requirements is known. Paper V tests the proposed method with the well known rule of thumb, the 3 “S”, meaning Safety, Space and Structure for construction schedule development and indicates health and safety of workers and the flow line method as new requirements for a good quality project schedule. In particular, the specific contribution of paper V concerns safety requirements of the construction schedule, that is an original contribution of the present research work to the developed 75 detailed requirement list. In the final version of the Schedule Health Assessment procedure a unique detailed requirement termed “safe & non-congested work areas” has been included, consisting of two specific requirement specifications: safety and hazard space; and non-congested work areas. A more in deep description of this part of the research work is following.

4.2.1 Construction process and safety requirements

As already mentioned, the quality indicator concerning construction process has been changed in progress with the introduction of a new safety-oriented requisite. In paper IV, the construction process requirements indicator for the schedule health assessment is introduced for the first time, and between others the requirement of construction process productivity is divided into three detailed requirements: work-continuity; work-flow; non-congested work areas (table 4.2).

Table 4.2 Construction Process Requirements (paper IV).

Schedule Health Indicator	Requirements	Detailed requirements
Construction process		
Requirements		
(omitted)		
	Construction process productivity	
		Work continuity
		Work-flow
		Non-congested work areas

Ballard (2000) indicates that a waste factor in construction is the lack of safety, therefore a safety – related requirement of a construction schedule is of capital importance. Nevertheless, the essence of a safety –oriented schedule is in avoiding time-space conflicts (Akinci et alii, 2002; Ciribini and Rigamonti, 1999, Sacks, Rozenfeld and Rosenfeld, 2009) and the well known “3S” rule-of-thumb by Callahan, Quackenbush and

Rowings (1992), meaning safety, space and structure has been taken as starting point for paper V. Therefore, the essence of a safety – oriented requirement for a construction schedule is to consider the spatial dimension of production process. In the development of paper V, the construction process productivity requirement has been improved into “Construction Process Safety and Productivity” to address both productivity and health and safety of workers. The schedule health indicators described in paper V are the following (table 4.3).

Table 4.3. Schedule Health Indicators - part 1 (paper V).

Schedule Health Indicator	Requirement
1. General Requirements	Schedule process procedure Schedule definition Activity definition
2. Construction process requirements	Activity sequencing & Structure adequacy Activity duration; Activity timing Construction process safety & productivity
3. Schedule mechanics requirements	Network and logic Critical path Float Soft & hard Constraints, buffers Activity mis-assignments Lag & lead (negative lag)

The construction process safety & productivity requirement is composed by the following detailed requirements (paper V):

- safety / hazard space;
- non – congested work areas;
- work continuity;
- work flow (safe, orderly and organized).

Herein there are three safety related requirements: safety/hazard space, non – congested work areas, and work flow (safe, orderly and organized). Then, in paper VIII the two detailed requirements were joined for simplicity sake:

- safety / hazard space;
- non – congested work areas;

A unique detailed requirement termed “safe & non-congested work areas” has been implemented in the final version of the Schedule Health Assessment procedure (paper VIII) to simplify the check list, but really the requirements are still two, because they can be found in the more detailed level of the requirement specifications. In fact, in the final version of the proposed method described in paper VIII the hierarchical

structure of the requirements is the following: requirements, detailed requirements and requirements specification (table 4.4).

Table 4.4 Construction Process Requirements (paper VIII).

Schedule Health Indicator	Requirements	Detailed requirements
Construction process Requirements (omitted)		
	Construction process safety and productivity	Work continuity Work-flow Safe & non-congested work areas

4.3 Scheduling as a quality creation function (RQ #2)

Answers to RQ #2 developed an approach to understanding construction quality and to measuring construction quality production in construction projects. Project control needs to develop a schedule model to perform its control processes, and paper I classifies schedule models into project oriented and process oriented, with a detailed analysis of the KPIs that can be delivered by each method. Then the quality issue is analysed in project control processes and paper II proposes the use of a Quality Breakdown Structure (QBS) for quality control and delivery (El Rayes, Kandil, 2006). Paper II is thought to be the first to propose the use of a process-oriented QBS in construction projects. The leading idea is that project quality delivery should be assessed for both construction process and schedule management.

The Quality Breakdown Approach has been previously tested in two case studies: a simple case study of a retrofitting project of two buildings of a public institution, which is the one presented in paper II, and in a case study of a residential building project of 40 apartments in a dwelling project near Rimini (Italy) shown in figures 4.2 and 4.3, but not mentioned before in this dissertation (Bernardi, 2012). More references can be found in the two unpublished building engineering thesis (in Italian) of which the author was the academic supervisor. The cited references can be found in paper II:

- [7] Baraghini A. (2006) "Il piano della qualità nel cantiere di lavori pubblici: aspetti normativi e operativi" Unpublished thesis in Building Engineering, University of Bologna.
- [8] Bernardi T. (2012) "Il controllo integrato di tempi/costi/qualità nei cantieri edili: caso di studio" Unpublished thesis in Building Engineering, University of Bologna.

With no reference in the dissertation, the author has spent many years since 1999 in research works concerning quality assessment of work packages of a building project in the Department of Architecture of

the University of Bologna (Bragadin, 1999. "Quality management in edilizia" INARCOS n.598 aprile 1999 pp. 193-200).



Fig. 4.2: Residential building project (after Bernardi, 2012).

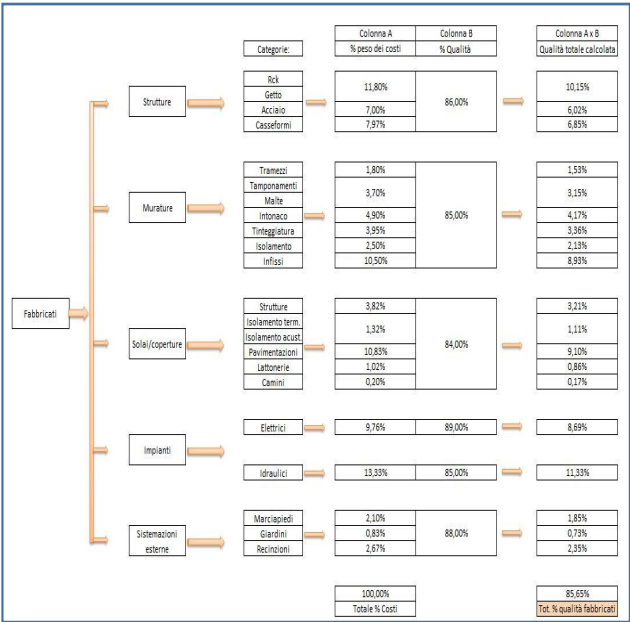


Fig. 4.3: Sample Quality Breakdown Structure (after Bernardi, 2012).

4.4 Resource – space charts as means for improving activity network schedule quality (RQ#3)

The REPNET method for construction scheduling is proposed as a process-oriented method. The REPNET method further develops the resource-space charts for activity network plotting, with the aim of optimising work-flow in construction projects. Paper III presents a complete planning and scheduling method that can develop a process oriented construction schedule in three phases. Firstly, computing and maintaining the PDM-based “As Soon As Possible” project total duration but allocating the activity network on the resource-space chart, secondly, optimizing workflow with constant resources and finally, if needed, modifying resource loading of crews to reduce further idle times of crews. The REPNET heuristic entails an original algorithm created by the author of this dissertation (Bragadin, 2010). Paper VI proposes the use of the resource-space chart, based on a Location Breakdown Structure, to fulfil another fundamental construction schedule process requirement such as avoiding conflicts between activities (which can be time/space conflicts, congestion space, hazard spaces and damage conflicts). This schedule feature was not found in previous works (non BIM-related) and fulfils a specific quality requirement of construction schedules. Project control processes can be improved as the resource – space charts can give detailed insights into the project status. Paper VII proposes the use of the REPNET for project strategy identification presenting the benefits of a process – oriented approach for project management planning and optimization processes.

4.4.1 The development of the REPNET - Repetitive Networking Technique

The proposed Repetitive Networking Technique - REPNET method was developed independently by the author in 2009 to improve the existing networking techniques for construction project scheduling. In the period 2002-2005 the author was a project scheduler of a huge multimillion civil infrastructure project in Italy, working with primavera P.3.1, and after this experience he started working as a full-time researcher at the university. So, the problems of construction scheduling practice were well known since then. The past working experience was decisive for the author's future line of research, and therefore the dissertation addresses mainly networking techniques and the search to improve their quality, understood as process-oriented modelling. The flow-line method is seen in this context as another way to optimize and display the results of the network – based model.

The REPNET originated from a research work started in 2006, when the CIB world Conference was held in Rome. There the author met Professor Alan Russell and understood completely the importance of resource-based scheduling and of the flow-line approach for construction scheduling. Then, the REPNET method has been developed by the author and published in the proceedings of the 2009 Conference of the Italian association of academic researchers of building production, ISTEa (Bragadin, 2009). In 2010 the REPNET method has been presented in the CIB world Congress in Manchester (Bragadin, 2010). In the CIB 2010 conference the author got in touch with the Location-Based Management System, and understood definitively the importance of a comprehensive approach to construction scheduling and control, based upon the Location Breakdown Structure by Kenley & Seppänen (2010). After this, the research work about resource-based scheduling for construction has been developed further including the flow-line view, and the approach was presented in the MISBE 2011 conference (Bragadin M.A., Kähkönen K., 2011). In 2012 doctoral studies started in Tampere, and the leading idea was to understand quality of schedules for construction projects, as the author's thought was that there was a research line concerning the development of a quality schedule for a quality construction project. The REPNET approach was further developed and presented in a Construction Research Workshop organised by the author in Ravenna (Italy) in 2013. Paper III is part of the proceedings of the Ravenna workshop. The REPNET approach has been studied further in paper VI and VII.

In paper VI the REPNET approach has been studied to develop a workspace management approach, and in paper VII to understand construction strategy.

4.4.2 Comparison between REPNET and existing methods

The REPNET has been compared with the corresponding CPM schedule in each paper concerning REPNET (paper III, VI and VII) as the first phase of the REPNET is a CPM schedule where the activity network has been plotted on a Resource-Space chart with no algorithm modification (i.e. ASAP and ALAP are performed as usual). While LBMS is a flow-line based method with a CPM layered logic, the REPNET was developed basically as an activity network plotted on a resource-space chart, following the example of Yi, Lee and Choi (2002) and Moselhi, Hassanein (2004). The leading idea was not to create a method similar to LBMS, but to improve the quality of the traditional activity network – based schedule models. Main references and source of inspiration were the works by Professor Russell (Russell, Udaipurwala, Wong, 2006) by Harris in his book (1978), by Selinger (1980) and by El Rayes and Moselhi (1998).

The proposed REPNET method can be compared with the Location-Based Planning (LBP) system (Kenley and Seppänen; 2010) through a comparison of the underlying scheduling principles (Seppänen and Tommelein, 2015; Biotto, Kagioglou, Koskela, Tzortzopoulos, 2017). In the following the core concepts of the two methods are presented.

- The REPNET is based – upon a resource –space chart where a Precedence Network is plotted. Therefore, it is a Location & Resource – based planning system because activities are defined depending on locations and crews. The core concept of the method is the optimization of the Precedence Diagramming Method. Flowlines are used with this aim.
- The LBP is based upon Flowlines. A CPM layered logic links tasks and sub tasks, but the core concept of the method is the optimisation of the work flow with flowlines, i.e. lines representing activities on a Location – time chart. A CPM-based algorithm provides time computation of the schedule.

The Location-based planning assumes that there is a value in breaking a project down into smaller locations and using these to plan, analyses and control the flow of work through these locations. The aim of location-based planning is to plan for productivity, managing explicitly the continuity of work of resources and therefore protecting and optimizing production. The Location-based Planning System is based upon the following eleven elements (Kenley, Seppänen, 2010) that can be classified into three main principles: schedule model; risk related; and workflow optimization. A comparison with the proposed Repetitive Networking Technique, REPNET can be found in table 4.5 a), b), c) d) and e). In the following the location-based scheduling principles are classified.

Location-based scheduling principles:

- 1) Schedule model:
 - a. Location Breakdown Structure (LBS)
 - b. Logic links between activities and CPM network logic
 - c. Scheduling Algorithm
 - d. Project views
 - e. Activity definition and duration
 - f. Monitoring, control and updates

- 2) Risk related characteristics:
 - a. Buffers
 - b. Schedule risks analysis
 - c. Time-Space conflicts
- 3) Workflow optimization:
 - a. Workflow protection
 - b. Optimization algorithm

Table 4.5 a) comparison between LBP and REPNET

	Principles Elements	Location-Based Planning	Repetitive Networking Technique REPNET
1)	Schedule model		
a)	Location-Breakdown Structure (LBS)	<p>Location-Based Structure:</p> <p>Generally from one to six hierarchy levels.</p> <p>Each task is defined at a hierarchy level. Highest levels: locations where the structure can be built independently (e.g. individual buildings or independent part of a building). Middle levels: the work flow can be planned across locations (e.g. floors). Lowest levels: only one trade can work in the area (e.g. apartments, corridors)</p>	<p>Location-Based Structure.</p> <p>LBS identifies project space units with a K code</p> <p>Spaces are represented in a resource-space chart with the LBS lowest levels in the columns of the chart.</p>
b)	Logic links between activities and CPM network logic	<p>CPM – based network layered logic</p> <p>Activity On Node network (Precedence Diagramming). A layered logic is between tasks is structured with five different layers of logic links concerning external and internal logic, location based logic and standard logic.</p>	<p>CPM – based network logic</p> <p>Activity On Node network (Precedence Diagramming)</p> <p>Precedence Diagramming is plotted on a resource – space chart.</p> <p>Network logic links activities that are located in specific space units, performed by specific resources (crews).</p>

Table 4.5 b) comparison between LBP and REPNET

	Principles	Location-Based Planning	Repetitive Networking Technique REPNET
1)	Schedule model (continued)		
c)	Scheduling Algorithm	<p>CPM – Based scheduling algorithm (PDM).</p> <p>ASAP and Continuous: layered logic requires multiple iterations, total project duration can be modified due to work continuity requirement.</p> <p>ALAP (float calculation).</p>	<p>CPM – Based scheduling algorithm (PDM).</p> <p>ASAP (traditional)</p> <p>Total project duration is found and remain constant</p> <p>ALAP (float calculation)</p>
d)	Project views	<p>Flowline view,</p> <p>PDM network view,</p> <p>control chart: task-locations</p>	<p>PDM network plotted on a Resource – Space chart;</p> <p>Flowline view;</p> <p>Control chart: updated PDM on R-S chart</p>
e)	Activity definition and duration	<p>Task and subtask/detailed task/activities defined.</p> <p>Task: a sequence of activities in differing locations which can be done by a single crew or by multiple crews</p> <p>Sub-task: a task need to be split in some locations</p> <p>Task duration is based on location-based quantities and productivity factors</p>	<p>Task: set of repetitive activities performed by one or more than one crew for a work item, identified by I code.</p> <p>Repetitive activity: a set of activities performed by the same crew in more than one space unit, identified by IJ code.</p> <p>Activity: set of construction operation performed by a specialized crew or equipment in a space unit, identified by a IJ-K Code</p> <p>Activity duration is based on location-based quantities and labor-days</p>

Table 4.5 c) comparison between LBP and REPNET

	Principles	Location-Based Planning	Repetitive Networking Technique REPNET
1)	Schedule model (continued)		
f)	Monitoring, control and updates	Control chart: task & locations updates: alarms: early warnings of upcoming production problems Chaos control chart (locations) Production charts	Control chart: updated PDM network plotted on a resource-space chart; week status: activities completed; in progress; immediate succ.; scheduled; unavailable space.

Table 4.5 d) comparison between LBP and REPNET

2)	Risk related characteristics		
a)	Buffers	Time and Space buffers Buffers on critical path can increase the total duration of the projects. Buffer size is a function of variability of predecessors, dependability of subcontractors and total float on locations	Contingency buffers Contingency Buffers (CB) are placed at the end of every sub critical resource path to protect Time Critical Path from overruns, and at the end of the project to maintain the minimum project total duration (no increase of total duration)
b)	Schedule risk analysis	Monte Carlo simulation with estimated variability of duration of tasks and site productivity.	Indirect risk analysis by estimate of Idle Time Indicator (ITI) on a resource path
c)	Time-Space conflicts	Conflict detection by checking crossing lines in the flowlines (physical presence of multiple crews detection).	Conflict detection by checking crossing lines in the flowlines. Unavailable spaces/safety spaces are highlighted; Labour density limits per space units

Table 4.5 e) comparison between LBP and REPNET

3)	Workflow optimization		
a)	Workflow protection	Work continuity requirement. Continuous work in each task on multiple locations.	Work continuity requirement. Continuous work on a resource path if free float is available.
b)	Optimization algorithm	<p>LBMS algorithm forces tasks to be continuous regardless of their float.</p> <p>Layer 3 logic / flow logic includes the possibility to force tasks to be continuous, CPM forward and backward pass require multiple iterations.</p> <p>Total project duration is augmented in comparison to original ASAP.</p>	<p>Heuristics shifts activities within free float to respect ASAP total project duration: two phases</p> <p>I) Resource path optimization with constant resources</p> <p>II) Project Workflow optimization resource paths with idle time are optimized changing crew composition.</p>

4.5 Summary of the discussion of contributions of the research

In summary, the discussion of the contributions of the research has highlighted the following topics. As concerning schedule quality (RQ#1), the Schedule Health Assessment proposed method is based upon 75 detailed requirements detected by the evaluation of 156 existing requirements from literature, and with the addition of a new safety-oriented requirement (i.e. safe & non-congested work areas).

As concerning scheduling as a quality creation function (RQ #2), the approach to understanding and measuring quality production in construction projects is based upon the Quality Breakdown Structure. The Quality Breakdown Structure approach allows to use the project schedule as a project control method for quality production of construction products and processes.

The answer to the research question RQ #3, presents resource-space charts as a mean for improving the network model quality for construction scheduling. The REPNET method is presented and it compared with Location-Based Planning by Kenley and Seppänen (2010). More similarities than differences have been found between LBP and REPNET, as they share common principles concerning location-based scheduling. Mainly they both use a Location-Based Structure, a CPM based scheduling algorithm and Flowlines, but some differences can be highlighted mainly related to scheduling models and algorithms, risk related features and workflow optimisation.

- 1) Schedule model First of all the LBMS is a Flowline-based scheduling model that includes a layered CPM network logic, while the REPNET is a CPM-based network model that entails a flowline view. In addition, the network representation of the REPNET is an AON plotted on a resource-space

chart, therefore being at the same time resource-oriented and space-oriented. The CPM-based scheduling algorithm of Location-Based Planning (LBP) has been modified because layered logic requires iterations, while the REPNET uses the traditional activity network time computations.

- 2) Risk related characteristics. Buffers in the LBP are placed in the critical path and have the aim of increasing project total duration in a risk management perspective. In addition, buffer size is function of the variability of predecessors, of the dependability of subcontractors and of total float on locations. In the REPNET instead, contingency buffers are placed at the end of every sub critical resource path to protect critical path from overruns, and at the end of the project to maintain the minimum project total duration (no increase of ASAP total duration). LBP also includes a Monte Carlo simulation in a risk management perspective, while the REPNET can perform only an indirect risk analysis by the estimate of idle time of crews on a resource path. Finally, concerning Time-space conflicts, LBP checks crossing lines in the flowline view, while in the REPNET unavailable spaces/safety spaces are highlighted and labour density limits per space units can be detected.
- 3) Workflow optimisation. Work continuity requirement is a stringent requirement in the LBP, while in the REPNET can be fulfilled only if free float is available. Therefore, the ASAP total duration is augmented by the LBP because it forces activities to maintain work continuity. In the REPNET instead, ASAP total duration is maintained.

The comparison of the two methods shows that they pursue the same aim with different perspectives. The LBP has also been developed with a well-known dedicated software, while the REPNET can be implemented with a traditional CPM-based software with some basic improvements.

5. Conclusions

5.1 Summary of the results

The aim of the research was to study and understand quality driven scheduling in construction projects. Schedule and scheduling quality is understood as composed of three main components defined in the research questions and results: quality of schedule and scheduling process; construction quality delivery in project control; and the most suitable approach for construction scheduling. These results, seen as a whole could enable the production of high quality scheduling and project control for construction projects with the assumption that construction schedule quality can contribute to project success by facilitating process design and control (Griffith, 2005; GAO, 2012). Next, the results of the papers will be interpreted as to understand their contribution to the dissertation's aim. The findings have the aim of understanding quality of schedule and scheduling, and the possible contribution of scheduling to project control..

Project control processes can be construction-oriented by creating a good schedule model of the planned and scheduled project (paper I). A quality oriented project control needs the implementation of a specific method, the Quality Breakdown Structure (QBS). The QBS detects product and process quality, and therefore can be strictly related to project scheduling and controlling, and to production process in construction (paper II). The construction process needs construction – oriented scheduling and the REPNET method, in which a resource-space chart is used to plot a PDM – based network, has proven to be a suitable approach for workflow optimization, as it is a process-oriented schedule (paper III). However, five classes of requirements should be fulfilled by a schedule to obtain a good quality construction programme. These classes are termed Schedule Health Indicators, namely: general requirements about project scheduling, construction process requirements, schedule mechanics requirements, cost and resources requirements, and control process requirements (paper IV). Beyond this, there are the fundamental requisites of a process-oriented schedule for a construction project, Safety, Space and Structure (this is the “3S” rule of thumb by Callahan et alii, 1992), and in addition to this, the schedule itself needs to be presented with a flow-line view to highlight possible space conflicts. Therefore, the flow-line view itself is to be considered a quality requisite of the schedule model, and the construction process requirements of the proposed Schedule Health Assessment method have been improved including health and safety of workers(paper V).

Resource-space charts and the flow-line views of the REPNET method constitute the basis of a good quality schedule for a construction project, facilitating process modelling, work-space management, and project control (paper VI). In addition, the REPNET approach can be suitable for defining construction strategy and the comparison of different scenarios, especially in a building rehabilitation project, where workspace constraints are of paramount importance (paper VII). Finally, after the identification of 156 different detailed requirements for construction scheduling from pertinent literature, scheduling standards, scheduling practice and further research work developed in paper V, a set of 75 detailed requirements has been identified. Detailed requirements have been grouped into the five health indicators, and a procedure of Schedule Health Assessment has been developed. The Schedule Health Assessment proposed method has the twofold goal of performing a quality assessment of a construction schedule and of being a guide for the project team in developing the schedule and executing schedule management for project control purposes. Different indicators can be selected to evaluate the planning phase and the controlling phase (paper VIII).

5.5.1 Contributions of the research

The findings indicate that project control processes, starting from planning, to scheduling and controlling can be based on a good quality project schedule that can facilitate project management activities, and can be linked to the project management quality control function, therefore including in the schedule model all the KPIs of the iron triangle, time, cost and quality (Atkinson, 1999). The results can be further divided into the three related research questions addressed in the dissertation:

- Research Question # 1: what is schedule quality?
- Research Question # 2: what is scheduling producing in terms of quality?
- Research Question # 3: can the activity network schedule model be process-oriented and quality driven?

The following answers to the research questions were found in the dissertation (fig. 5.1).

- Research Question # 1: what is schedule quality? Schedule quality is the fulfilment of many schedule requirements, with the aim of satisfying the needs of work structuring of construction process and of scheduling mechanics. The study of literature has revealed that several approaches exist (De La Garza, 1990; Russell, 2000; PMI, 2007; Moosavi, 2012), but few of them are construction-oriented and usually tend to neglect the scheduling process assuming only a control function. An answer to this question and to the research gaps was given in the dissertation through the development of a method to understand, develop and measure Project Schedule Quality in Construction. The proposed method is termed "Schedule Health Assessment". The Schedule Health Assessment process quantifies schedule performance, thus enabling the project team to implement a proactive approach to construction scheduling. The Schedule Health Assessment proposed method is based on 75 detailed requirements grouped into five Schedule Health Indicators (paper IV and VIII). The 3 "S" rule for construction scheduling, meaning "Safety, Space and Structure" (Callahan, Quackenbush, Rowings, 1992) was used to synthesise quality requirements of the construction process and test the proposed procedure, as the process design implemented through schedule model has to satisfy the 3 "S" rule to obtain a good quality schedule. Safety and structure requirements can be fulfilled through activity sequencing, i.e. network logic. Space, i.e. a location & resource-based production organisation system (Kenley, Seppänen, 2010) is believed to be the answer to the need for creating a construction-oriented model for scheduling and the essence of safety-oriented requirements of scheduling (paper V). In addition to this, the flow-line view is considered to be a quality requisite of the schedule model.
- Research Question # 2: what is scheduling producing in terms of quality? Project schedule is the basis for project control, as it controls the delivering of time (meaning the progress of activities) and costs. Therefore, process and product quality should be fully included in project control, and quality should be delivered and controlled by project schedule. Previous work has focused the relationship between time, cost and quality objectives as the main concept of project management processes and the need of quality based KPIs (Atkinson, 1999; El-Rayes, Kandil, 2005; BCA, 2008), but no attempt was made to fully integrate quality in the scheduling and controlling process. In fact, usually quality control in construction is managed in a separate way from time and cost control. Although, these three project objectives are interdependent and process and product quality management should be fully included in project control. An answer to this question was proposed in the dissertation developing an approach to understanding and measuring quality of production in construction projects. The proposed method is based upon the definition of a "Quality Breakdown Structure (QBS)". The Quality

Breakdown Structure quantifies project quality performance through specific quality oriented KPIs, and therefore the project team can implement a proactive approach to quality of construction production by integrating quality in project scheduling with the QBS (paper II). In addition to this, it is proposed to improve the quality of Project Control processes by implementing a process-oriented schedule modeling (paper I).

- Research Question # 3: can the activity network schedule model be process-oriented and quality driven? The activity network creates the logic of work structuring. Work structuring in construction should optimise workflow mainly considering the limitations of resources and spaces, meaning crews, equipment and working locations. The study of previous work has highlighted a criticism of the network-based approach for construction scheduling (Koskela, 1992; Russell and Wong, 1993, Kenley and Seppänen, 2010) and indicated three main components of a construction-oriented schedule: a) time-space charts; b) linear scheduling methods, flow lines and optimization algorithms; c) lean process implementation and automation in project scheduling (Selinger, 1980; Birrell, 1980; Russell and Caselton, 1988; Moselhi and El-Rayes, 1993; Russell and Wong, 1993; Suhail and Neale, 1994, Kähkönen, 1994; El-Rayes and Moselhi, 1998; Kenley and Seppänen, 2010). In summary, the proposed solutions aim at improving the network – based approach for construction project scheduling to take account for flow. The improvement necessitates different algorithm and software and may not be suitable in traditional contractual environment, actually abandoning the traditional network-based approach though its widespread use for project management in the construction sector. An answer to this research question can be found in the dissertation through the further development of a network-based scheduling method that plots the activity network on a resource – space chart. The proposed method, termed Repetitive Networking Technique (REPNET), is a process-oriented heuristic construction scheduling approach where the activity network model (in the form of Precedence Diagramming) is plotted on a resource-space charts and displayed with a flowline (paper III). The REPNET creates a quality driven and construction-oriented schedule model for phase or detailed project scheduling that maintains the found ASAP total project duration and protects work continuity of resources if free float is available. Workspace scheduling, control, and project strategy can be easily implemented with the REPNET, and quality requirements about construction logic, safety and workspace management can be easily fulfilled (paper VI and VII).

In its entirety, this dissertation suggests that quality driven scheduling for construction project can be improved by the implementation of a good quality schedule, by the integration in project control processes of the delivered quality KPIs and by a process-oriented scheduling. Therefore, quality driven scheduling can be better achieved with the proposed methods, meaning the Schedule Health Assessment approach, the Quality Breakdown Structure, and the REPNET method, and it makes the following proposals:

1. Project teams of owners and companies should deliver and check construction schedule quality, to endorse project success achievement. The Schedule Health Assessment proposed method can be a suitable approach especially for Small and Medium Enterprises of the construction industrial sector as it is based upon a simple set of five check-lists.
2. Project schedulers of owners and construction companies should use resource-space charts as a base for developing common network-based schedules even if implemented with commercial PDM-based computer software, if they do not wish to implement a new scheduling system requiring new software, such as LBMS. In particular, the REPNET method could be very useful in creating project strategy, in developing master and phase schedules, in performing project control and workspace management of construction projects. REPNET is, in fact, a process-oriented scheduling method that includes activity dependencies, resource paths through project locations, flow-lines view and Location Breakdown Structure. All of these components are suitable and needed for the quality of the modelling of the construction project. These features increase their importance in existing

building refurbishment / rehabilitation projects because of the major influence of space constraints and workspace management processes.

3. Project Control should improve its contribution in building and construction quality management. The delivery of time, cost and quality objectives should be managed through project scheduling. Therefore, a Quality Breakdown Structure needs to be created and used to understand and evaluate the produced quality, assuring that the end products meet all the project objectives.

The results of the dissertation suggest that, by using the aforementioned methods, the construction management process can rely upon sound and robust models for schedule production, schedule management and project control implementation.

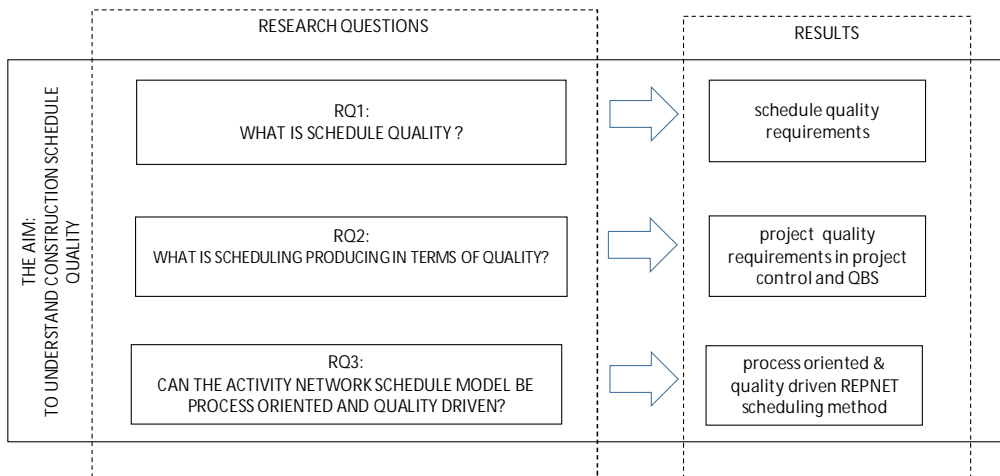


Fig. 5.1: Results of the research

5.2 Evaluation of the research

Qualitative and constructive research can be evaluated based on its reliability and validity (Eriksson P., Kovalainen A. 2008; Scotland, 2012). Reliability is one of the classic evaluation criteria commonly used in qualitative research. Reliability evaluates whether the same conclusions are repeatable (e.g. experiment). The reliability of the results was increased by including case studies in each presented paper. Apart from Paper I, which is based mostly upon a literature review, each paper includes a case study or a sample application drawn from real construction projects with the aim of testing the constructed method. Case studies are used to test the proposed methods included in each answer to research questions.

The validity of the research evaluates the capacity to move scientific knowledge forward. Internal validity/credibility concerns with the coherence of the research and the proper application of the method.

External validity/transferability refers to generalization of results outside the research setting. Constructed internal validity/credibility of the dissertation aiming at understanding construction quality in scheduling was improved by using three different approaches to the understanding of quality driven scheduling in construction:

- the fulfilment of a set of selected detailed requirements was the approach of the answers to RQ#1
- the classification and evaluation of product and process quality in project control via the creation of a Quality Breakdown Structure was the approach of the answers to RQ#2
- the creation of a process-oriented schedule model, including resource and space constraints on a PDM – based activity network, the REPNET method, was the approach of the answers to RQ#3

Not included in this dissertation are several case studies in which the quality of a construction schedule has been implemented dramatically simply applying the DCMA 14 points quality standard (DCMA, 2012) or the Schedule Health Assessment process proposed by the NDIA (2012) in the PASEG guide.

Concerning external validity/transferability, the constructed proposed methods can be easily replicated in other construction projects, and therefore the results can be generalized to the industrial sector of building construction. In particular, all case studies were located in Italy, but as detected in pertinent literature from Finland and other countries, it can be argued that the understanding of schedule quality and construction quality in project control are common problems worldwide in the construction industry.

5.3 Limitations of the research

The aim of the whole research work is to study schedule quality and propose some possible research lines to understand better the scheduling approach and context for construction project. No best solution to solve construction scheduling problem is found, but three approaches to mitigate some of the critical issues are being proposed.

The research is based on the constructive research method. Therefore, most of the focus is on the development of new models “constructions” or “artefacts” in constructive approach. The detection of problems has been performed thorough literature study and personal experience of the author when he acted as project scheduler. Research gaps and comparison of proposed models are described in the dissertation (par. 2.2 and 2.3 and chapter 4).

Limitations of this dissertation include the following:

- the Schedule Health Assessment approach relies on five Health Indicators whose weights need further testing in future research; only a great amount of testing on construction projects could give sound reliability to the assessed weights of each class of requirements;
- the proposed REPNET method was tested on rather simple projects. In complex projects, hand computing should be substituted with an automated system, i.e. software program; the same limitation applies to network creation on the resource – space chart and flowline plotting;
- only five case studies were used to test the proposed methods. Even so, it is thought that case studies were part of a representative sample of real – life small/medium – sized construction projects of the Italian building construction sector;

- the building projects in the case studies were located in Italy, although the common features of construction process and sector suggest that generalization to international building construction sector is possible.

5.4 Future research

This dissertation indicated three lines of research and suggestions on improving the understanding and development of quality driven scheduling for construction projects.

The first research line is related to the Schedule Health Assessment proposed method. It is suggested that Schedule Health Assessment can improve Schedule Management processes in construction projects that often suffer from scarce resources allocated for the Planning and Scheduling functions, leading to poor planning and scheduling. The proposed Schedule Health Assessment method is simple to implement because it is based on five checklists that allow the scheduler to perform a quick evaluation of the produced schedule. Therefore, the checklists can be used as a guide for the whole schedule management process. Further research will develop a step-by-step procedure for schedule creation, based upon the 75 detailed requirements, and the fine tuning of weights of the five indicators that contribute to the quality assessment based upon feedback from actual projects.

The second line of research could be the development of a software program that implements the REPNET heuristics. In the papers, the efficiency of the REPNET method as a construction – oriented scheduling approach has been presented and discussed. A software program can perform the automated computation of activity times and can support the resource-space network creation, and the corresponding flow-line plotting and control charts creation. Therefore, the development of a new computer software program or better, the development of a new version of an existing network-based software that incorporates flow can increase dramatically the efficiency of the scheduling process. Also, the integration of the LBMS and REPNET approaches could enable the application of the REPNET method to complex projects and the benefits of using float vs. continuous work should be further explored. . In particular, there is a perspective of further schedule model improvement taking into account vertical logic links, in addition to the horizontal dependencies already included in the model (Kähkönen, 1994; Kenley, Seppänen, 2010). The comparison of a traditional schedule with the corresponding REPNET schedule of the same project with the proposed Schedule Health Assessment procedure can give new insights into both the Health Assessment method and the REPNET.

Finally, as a third line of further development of the research, the QBS approach in project scheduling and control could be performed for many other projects with the aim of testing the method. Quality creation during project execution can be evaluated through the development of the Quality Breakdown Structure and its loading upon scheduled activities. This has proven to be an efficient process for quality control, but the delivery of the 100% of the promised quality is difficult to achieve. This is mainly due to the re-working of defective components. While in a process perspective this is always a process fault that will not be recovered entirely, in a product perspective a complete recover of the promised quality can be achieved (in some cases!). Further testing via other new case studies could be useful for the understanding of the quality creation process in construction and its scheduling and controlling.

The aim of this dissertation was the understanding of the quality driven scheduling process in construction projects, with the idea that the generation of a quality schedule can be a useful tool for the project team in the planning and controlling process. The automation, or better the semi-automation via an expert model (Kähkönen, 1994), of the scheduling creation process can be the next, and future, horizon of

construction project management. Therefore, the proposition of an integrated approach composed of these three methods, namely Schedule Health Assessment, Quality Breakdown Structure and Repetitive Networking Technique could be a step forward to the solution to schedule quality problems in construction projects.

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Annexes

Appended papers I - VIII

Innovation in Construction Project Control

by Bragadin M. & Kähkönen K. (2013). Proceedings of ISTE A 2013 Conference "ICT, Automation and the Industry of the Built Environment: from the Information Exchange to the Field Management" Politecnico di Milano, October 3rd – 4th, Milan Italy, Maggioli S.p.A. pp. 138-157. ISBN 88-387-6258-1

INNOVAZIONE NEL CONSTRUCTION PROJECT CONTROL

INNOVATION IN CONSTRUCTION PROJECT CONTROL

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Topic: 7. il project construction management ed i sistemi integrati di gestione.

Abstract

Construction control is an essential management function for successful delivery of construction projects. For the Project Management Body of Knowledge the control process compares actual performance with planned performance, analysing variances, assessing trends to effect process improvements, evaluating possible alternatives and recommending appropriate corrective action as needed. A variance is a quantifiable deviation, departure or divergence away from a known baseline or expected value. So, construction control can be divided in the monitoring phase that detects variances, and the control phase that recommends proper corrective actions.

Actually main goal of Project monitoring process is the measure of project performance. The measurement of the performance of a construction project can be achieved through technical testing and professional observations and through the use of metrics such as Key Performance Indicators (KPIs). KPIs are intended to represent the health of the construction project and can be used to predict the future project performance by means of an ICT – based model, e.g. activity network or a flow-line chart, implemented with a proper controlling technique. So the measure of project performance is actually in profound relationship with project models beyond project control technique.

With this point of view the traditional Project Control approach is compared with the innovative Production Control approach for construction. In particular most used ICT – based project oriented controlling techniques, ie scheduling models and Earned Value Method, are compared with production oriented techniques ie the Last Planner System, the Critical Chain Method and the Location - Based Management System.

This paper shall provide a review of ICT-based construction project control methods and discuss their benefits and limits to explain the performance of modern construction controlling processes.

1. Introduzione

Il construction control è una funzione manageriale essenziale per il successo di un progetto nel settore delle costruzioni. La gestione di un progetto di costruzione richiede infatti una sempre maggiore consapevolezza dei sistemi di Project Control, per assicurare che i progetti di qualsiasi dimensione siano completati nei tempi e nei costi previsti e con la qualità richiesta, poiché i frequenti scostamenti nella fase esecutiva rendono sempre più difficile il completamento del progetto e il raggiungimento degli obiettivi posti a base dell'intervento.

La prestazione del progetto deve quindi essere misurata con regolarità per identificare gli scostamenti da quanto pianificato e programmato (PMI, 2004). Il Project Management Institute, PMI, definisce il controllo del progetto, Project Control, come il processo di comparazione tra la prestazione effettiva del progetto e la prestazione attesa da programma, il processo di analisi degli scostamenti e di valutazione delle alternative possibili, e l'esecuzione delle necessarie azioni correttive. Lo scostamento è definito come una deviazione quantificabile da un riferimento noto o da un valore prestazionale atteso. Il Project Control è fondamentalmente sviluppato in due fasi, la fase di monitoraggio e la fase di controllo vero e proprio. La fase di monitoraggio ha l'obiettivo di analizzare e registrare la prestazione del progetto effettiva in relazione a quella attesa, ed è intrapresa per definire lo stato del progetto ed il suo avanzamento. E' chiaro che il monitoraggio ha significato solo in relazione alla prestazione attesa da programma. Lo stato del progetto infatti può essere definito come una variazione da quanto pianificato nell'area dei costi, dei tempi, dell'ambito del progetto, della qualità e del rischio.

1. Introduction

Construction control is an essential management function for successful delivery of construction projects. Construction Project needs an increasing awareness of project control management systems, to assure that projects of all sizes are completed on time, on budget and with the required quality, in fact frequent variances accentuate the urgency of project completion and project goals achievement. Project performance must be measured regularly to identify variances from the plan (PMI, 2004). PMI defines Project Control as the process of comparing actual project performance with planned performance, analyzing variances, evaluating possible alternatives and taking appropriate corrective action as needed. A variance is a quantifiable deviation, departure or divergence away from a known baseline or expected value. Project control is basically performed in two phases, the monitoring phase and the control phase. The monitoring phase incorporates the tasks of capturing, analyzing and reporting project performance compared to plan. The monitoring action is taken to assess project status or progress. It is clear that monitoring is meaningful if can be compared with that which was expected. Project status in fact can be defined with variances from plan in the areas of cost, time, scope, quality and risk. While monitoring is to picture what is happening on a project, the control phase involves the determination of actions to response to monitoring results, i.e. changes to make to bring expected future performance of the project into line with plan (PMI, 2004).

Mentre il monitoraggio rappresenta quello che sta succedendo al progetto, la fase di controllo comprende la determinazione delle azioni da intraprendere in risposta ai risultati del monitoraggio, ovvero le varianti da eseguire per riportare la futura prestazione del progetto in linea con quanto pianificato (PMI, 2004).

1.1 Monitoraggio e Controllo del progetto tramite ICT e KPIs

La misurazione della prestazione di un progetto di costruzione può essere svolta tramite verifiche tecniche e test sulla produzione e tramite l'uso di una specifica metrica di progetto definita da Indicatori Chiave di Prestazione (Key Performance Indicators – KPIs).

I KPIs hanno l'obiettivo di rappresentare lo stato di salute del progetto di costruzione e possono essere utilizzati per predire la futura prestazione del progetto tramite un modello di Information e Communication Technology (ICT) computerizzato, come un reticolo di attività elementari o diagramma flow-line, integrato con un idoneo metodo di controllo.

Le tecnologie ICT utilizzate nell'industria delle costruzioni sono le più varie e spaziano dalle applicazioni più generali per la scrittura ed il calcolo, per la gestione economica, per l'archiviazione dei dati, per la gestione delle risorse umane, per il rilievo, per il disegno e la progettazione (CAD), per la presentazione e per la comunicazione ed il marketing, sino a quelle per la pianificazione ed il controllo. In particolare la funzione di pianificazione e controllo utilizza software per la schedulazione per definire i processi e la durata del progetto (Murray, Arif, Lai, 2002).

Tradizionalmente la prestazione di un

1.1 ICT-based Project monitoring and control with KPIs

The measurement of the performance of a construction project can be achieved through technical testing and professional observations and through the use of metrics such as Key Performance Indicators (KPIs).

KPIs are intended to represent the health of the construction project and can be used to predict the future project performance by means of an Information and Communication Technology (ICT) – based model, e.g. activity network or flow-line chart, and integrated with a proper controlling technique.

ICT in construction industry is widely implemented, starting from general – purpose applications for word processing and for computing, for accounting and financial management; for archiving, for human resource management, for surveying, for drafting and design (CAD), for presentation purposes and communication, for marketing purposes, ending with project planning. In particular project planning and control employs scheduling software for establishing project's processes and duration (Murray, Arif, Lai, 2002).

Traditionally the performance of construction projects is measured by means of three classes of performance indicators: cost, time and quality. Recent

progetto di costruzione è misurata tramite tre categorie di indicatori di prestazione: i costi, i tempi e la qualità. A queste la ricerca internazionale ha aggiunto altre categorie specifiche per il settore delle costruzioni. In particolare il Minister of Construction del Regno Unito (2000) ha identificato sei categorie di KPIs: i costi, i tempi, la qualità, l'igiene e la sicurezza, la prestazione imprenditoriale e le varianti in corso d'opera. D'altro canto Kumaraswamy e Thorpe (1996) hanno aggiunto a tempi, costi, qualità e sicurezza i seguenti KPIs: l'impatto ambientale, la soddisfazione del cliente e del team di progetto, il trasferimento tecnologico. Kerzner (2011) riporta i seguenti KPIs per i casi di studio della costruzione di Disneyland e Disney World: tempi, costi, ambito, sicurezza, valore estetico e qualità, con gli ultimi tre KPIs non passibili di negoziazione. Suk (et alii, 2012) per i progetti di costruzione di impianti farmaceutici ha incluso solo i seguenti KPIs: costi, tempi, qualità, sicurezza ed efficienza del progetto e dei caratteri distributivi.

E' chiaro come tutti i sopra descritti KPIs sono di importanza fondamentale per i processi gestionali della costruzione, ma gli scostamenti nella produzione sono fondamentalmente stimati in termini di KPIs legati ai tempi e ai costi che misurano le differenze tra il programma lavori iniziale e il budget preventivo con l'effettivo avanzamento delle fasi di lavoro ed i costi sviluppati. Quindi i processi gestionali di controllo devono essere basati su un solido programma lavori con allocazione dei costi, considerando l'interdipendenza di tempi e costi. E' utile notare che la definizione dei KPIs è fondamentalmente basata sul modello del progetto definito per il controllo, solitamente il modello per la schedulazione costruito per mezzo di uno strumento ICT, ovvero un software commerciale per la

research employed additional performance indicators to better evaluate construction projects. In particular the Minister of Construction of the United Kingdom (2000) identified six KPIs: cost, time, quality, health and safety, business performance and change orders. Instead Kumaraswamy and Thorpe, (1996), added to time, cost, quality, and safety KPIs, the following KPIs: environment impact, client and project team satisfaction, and technology transfer, while Kerzner (2011) reported the following KPIs for the case studies of Disneyland and Disney World construction projects: time, cost, scope, safety, aesthetic value and quality, with the last three being fixed values that could not be negotiated. Suk et alii (2012) for pharmaceutical construction projects included only the following KPIs: cost, time, quality, safety and design/space efficiency.

It is believed that all of the described KPIs are of great interest in Construction Management, but variance in production is basically evaluated in terms of time and cost KPIs that measure differences between planned schedule, budget and actual progress of working phases and inherent cost. So project control processes must be based on a sound project plan with cost allocation, considering the interdependence of time and cost.

It is important to note that KPIs definition is mainly based upon the project model built for control purpose, ie the scheduling model built by mean of an ICT tool, usually a commercial software for project scheduling and control.

So the measure of project performance is actually in profound relationship with ICT project model beyond project control method.

programmazione ed il controllo. Quindi la misura della prestazione del progetto è, in realtà, in relazione profonda con il modello ICT sotteso al metodo di controllo.

2. L'approccio tradizionale del Construction Project Control

L'approccio tradizionale al controllo dei progetti di costruzione è fondamentalmente orientato al progetto nel suo insieme, e mira a fornire le informazioni necessarie per il team di progetto per identificare e correggere le aree problematiche in relazione con la qualità, i costi e l'avanzamento del lavoro. In realtà questi temi sono trattati nel team di progetto in modo abbastanza separato, in particolare la qualità e il controllo della sicurezza sono spesso tenuti separati dal controllo dei costi e dell'avanzamento lavori, essendo in genere affidati a due o tre diverse persone responsabili. Fondamentalmente questo è perché l'obiettivo fondamentale della gestione del progetto di costruzione è la ultimazione dei lavori nei tempi e con i costi preventivati. Il team di controllo del progetto ha l'obiettivo di individuare gli scostamenti negativi dal programma lavori iniziale e dal budget preventivo in modo da intraprendere le necessarie azioni correttive.

2.1 I modelli temporali per il controllo del progetto

I modelli temporali per il controllo del progetto hanno l'obiettivo della misurazione dell'avanzamento dei lavori. I modelli fondamentali sono il diagramma a

2. Traditional approach to Construction Project Control

Traditional construction control approach is basically project oriented and aims at providing information needed for the project team to identify and correct problem areas, in relationship with quality, cost and work progress. Actually in construction project team these issues are treated quite separately, and in particular quality and safety control are often taken apart from cost and schedule control having two or three different responsible persons. Basically this is because main objective of construction project management is project delivery on time and within budget. Project control team has the objective of detecting negative variance from target schedule and budget, so corrective action can be taken.

2.1 Time-based project control models

Time – based project control models are aimed at progress measurement of project. Main models are the barchart/Gantt, Precedence Diagramming

barre / Gantt, il Precedence Diagramming Method e la tecnica Line of Balance o Flow-line.

Il diagramma Gantt è un semplice strumento di pianificazione e programmazione che da informazioni sulla lista di attività, la loro durata e i rispettivi tempi di inizio e di fine, le milestones e le date di controllo (Moder, Phillips, Davis, 1983). Quindi la misurazione della prestazione del progetto è basata su questo insieme di dati (tab. 1). A causa della mancanza di un algoritmo di schedulazione il modello a barre non è adatto per progetti complessi (fig. 1).

Il Precedence Diagramming Method (PDM) è una evoluzione molto nota del Metodo del Cammino Critico (CPM). Si tratta di uno strumento di pianificazione e programmazione basato su di un reticolo che da informazioni sulla lista di attività, le loro relazioni logiche, la loro durata e i loro tempi di inizio e fine, gli scostamenti disponibili e le attività critiche per i tempi (ovvero il tempo complessivo disponibile per svolgere le attività senza un ritardo nel completamento del progetto), le milestones e le date di controllo (Bragadin, 2011). La misurazione della prestazione del progetto è quindi relativa a questo set di dati (tab. 1). Poiché è dotato di un algoritmo di schedulazione è adatto a progetti complessi (fig. 2).

Method and Line of Balance technique / flow-line.

The Gantt chart is a simple planning and programming tool that gives information about the list of activities, their duration and their start and finish dates, the milestones and the monitoring dates (Moder, Phillips, Davis, 1983). So performance measurement of project status is about this set of data (table 1). Due to the absence of a scheduling algorithm the barchart model is not suitable for complex projects (figure 1).

Precedence Diagramming Method (PDM) is a well known evolution of the Critical Path Method (CPM). It is a network based planning and programming tool that gives information about the list of activities, their logical relationships, their duration and their start and finish dates, the available float and the time critical activities (i.e. the total time available to perform the activities without a time delay on project completion), the milestones and the monitoring dates (Bragadin 2011). So performance measurement of project is about this set of data (table 1). Due to the scheduling algorithm it is suitable for complex projects (figure 2).

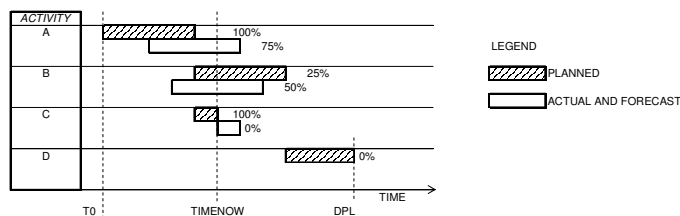


Figure 1: Control Barchart.

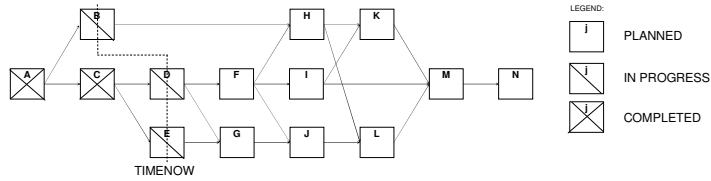


Figure 2: Control activity network (PDM).

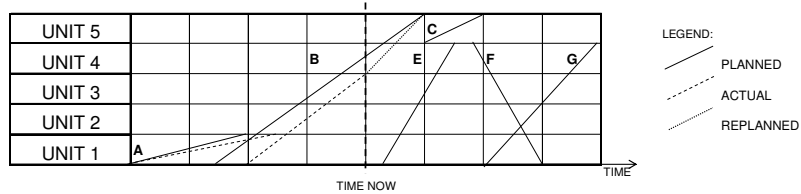


Figure 3: Control Line Of Balance (LOB) / Flow-line

L'impiego dei dati necessita di un pianificatore esperto in quanto si tratta di un modello complesso che è stato originariamente concepito e sviluppato come un sistema di controllo basato sulle ICT, al contrario del Gantt che lo è divenuto per mantenere la sua efficienza.

La Line Of Balance (LOB) nella forma flow-line è uno strumento di pianificazione e programmazione che oltre alle informazioni date dal Gantt fornisce la localizzazione spaziale delle attività (Uher, 2003), consentendo il controllo su questo set di dati (tab.1). A causa della sua struttura grafica è un modello adatto per progetti semplici e ripetitivi (fig.3). L'uso dei dati è molto semplice in quanto è un metodo grafico, ma è necessario un pianificatore esperto. A causa della complessità dei progetti di costruzione il suo utilizzo è grazie ai sistemi ICT.

I metodi di controllo basati sul tempo permettono la definizione di almeno sei KPIs nell'area della prestazione temporale, relativi al consumo dei tempi, allo stato di avanzamento, alle attività critiche, alla logica

The usage of data needs a skilled planner as it is a complex model which was originally conceived and developed as an ICT-based planning and controlling system. Barchart instead has become an ICT- based model to keep on efficiency.

The Line of Balance (LOB) in the flow-line view is a planning and programming tool that adds to the Gantt set of information the activity location (Uher, 2003), allowing control process on this set of data (table 1). Due to the graphical structure of the model it is suitable for simple repetitive projects (figure 3). The usage of data is very simple as it is an only graphical model, but a skilled planner is required. Due to construction project complexity its usage must be ICT – based.

With time - oriented control methods at least six KPIs can be defined in the area of time performance, related to time consumption and project completion, critical activities, construction logic, project location and resource

della costruzione, alle localizzazioni del progetto e alla produttività delle risorse (Tab.1).

2.2 Il controllo integrato tempi/costi con il Earned Value Method (EVM)

Il Metodo del Valore Guadagnato (Earned Value Method – EVM) è forse lo strumento principale del Project Control. Il concetto fondamentale del sistema EVM è il controllo integrato tempi/costi e la conseguente definizione di KPIs che consentono un approccio quantitativo al monitoraggio, controllo e riprogrammazione del progetto. Lo strumento fondamentale del metodo EVM è la Work Breakdown Structure (WBS) struttura analitica del sistema di informazione e integrazione del progetto (Moder et alii, 1983, Rasdorf and Abudayyeh, 1991) (fig.4). La WBS è una scomposizione gerarchica, orientata ai deliverable, del lavoro da eseguire in pacchetti di lavoro (Work Packages, WP) che organizza e definisce l'ambito totale del progetto (PMI, 2004). La WBS ha l'obiettivo di fornire una struttura integrata per il controllo dei tempi e dei costi dei WP, ma in pratica l'approccio della WBS al controllo di tempi e costi non è facile da sviluppare con successo. E' infatti molto difficile ottenere una scomposizione del lavoro che definisca in modo conveniente sia la quantità di tempo che la quantità di costo. Infatti, in generale, il dettaglio che è richiesto per un controllo adeguato dei tempi è troppo accurato per il controllo dei costi, rendendo difficile il processo di allocazione dei costi o viceversa. L'interazione tra la Organization Breakdown Structure (OBS) e la WBS assegna le responsabilità dei WP ai rispettivi elementi organizzativi. L'interazione può essere visualizzata come una matrice con gli elementi dell'organizzazione funzionale

productivity (tab.1).

2.2 The time/cost project control of the Earned Value Method (EVM)

Earned value method is the main tool that accomplish traditional project control. Basic concept of Earned Value Management System is the focus on the integrated time/cost project control, and the subsequent definition of project KPIs for a quantitative approach for project monitoring, controlling and forecasting. Core tool of the EVM is the Work Breakdown Structure (WBS) that is the structure of the project information integration system (Moder et alii, 1983, Rasdorf and Abudayyeh, 1991) (figure 4). The Work Breakdown Structure is a deliverable-oriented hierarchical decomposition of the work to be executed into Work Packages (WP) that organizes and defines the total scope of the project (PMI, 2004). The WBS is meant to provide an integrated framework for time and cost control of WP, but in practice the WBS approach to time and cost project control it is not easy to successfully develop. It is very difficult to obtain a breakdown of the work into activities which represent both the most convenient time and cost quantities for control purposes. In general the detail which is required for adequate time control provides too much detail for cost allocation, making difficult the cost allocation process, or vice-versa. The interaction between the Organization Breakdown Structure (OBS) and the WBS assigns work responsibility to appropriate

della OBS sull'asse delle ordinate e i relativi elementi della WBS sulle ascisse e l'intersezione tra questi due elementi è il punto di controllo (fig. 4). Il PMBOK (PMI, 2004) definisce il punto di controllo come il punto della WBS in cui si verifica l'integrazione dell'ambito, del budget, del costo effettivo e dei tempi, e dove si svolge la misurazione della prestazione di progetto.

organizational elements. The interaction may be visualized as a matrix with the functional organization elements of the OBS listed in one axis and the applicable WBS elements listed on the other. The intersection between these two elements of the chart is the original cost account, now known as control account or control point (figure 4). The PMBOK (PMI, 2004) defines the control account as the point of the WBS in which the integration of scope, budget, actual cost, and schedule takes place, and where the measurement of project performance will occur.

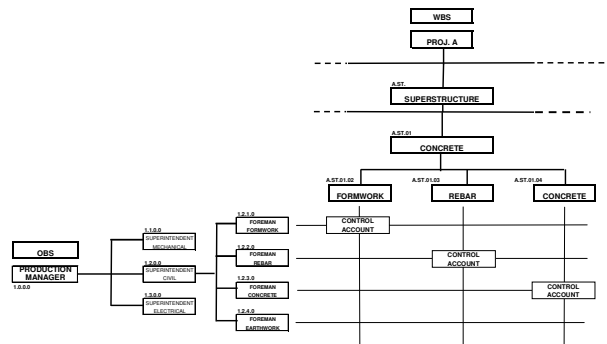


Figure 4: WBS: Working Package Approach (Rasdorf et alii, 1991)

L'EVM (ANSI/EIA, 1998) è uno strumento di pianificazione e programmazione dei costi che da informazioni riguardo ai costi preventivati, ai costi effettivi ed al valore guadagnato in relazione con i tempi di realizzazione del progetto. La misura della prestazione dello stato del progetto può utilizzare, oltre ai consueti KPIs relativi ai tempi, i KPIs relativi agli scostamenti di tempi e costi (e del loro rapporto) e indici di prestazione di progetto (tab. 1). Nella fase di ri-programmazione la prestazione prevista del progetto è sviluppata con questi dati e tramite l'estrapolazione lineare delle curve a S dei costi rispetto al tempo del progetto. Il

The EVM (ANSI/EIA, 1998) is a cost planning and programming tool that gives information about budgeted cost, actual cost and earned value in relationship with time of project development.

Performance measurement of project status is mainly performed through the following KPIs: time and cost variances (and their ratio); project performance indexes (table 1), in addition to ordinary time-related KPIs. In the re-planning phase the forecasted project performance is developed with this information and linear extrapolation of cost curves on a

valore previsto dei tempi e dei costi è stimato con semplici formule basate sui trend di progetto. Il metodo è adatto ad ogni tipo di progetto ma effettivamente si tratta di un sistema di gestione tecnico basato sui costi e sulle ICT, utilizzato per progetti di costruzione complessi e internazionali.

3. L'approccio del Production Control nella costruzione

Un progetto di costruzione è un processo produttivo temporaneo composto da molti sotto-processi con l'obiettivo di creare un'opera edile o di ingegneria civile. Quindi il controllo di progetto mira a monitorare e controllare l'avanzamento dei lavori in relazione all'obiettivo finale, mentre il controllo di produzione ha l'obiettivo di guidare il processo produttivo (o i sotto-processi), concepito come un flusso di materiali, attrezzature, forza lavoro, lavoro e informazioni, conformemente al progetto operativo e alle specifiche di qualità (Ballard, 2000). Il controllo tradizionale dell'avanzamento del progetto è totalmente orientato alla realizzazione e consegna degli obiettivi del progetto e ai processi di conversione definiti dalle attività della WBS. Questo approccio al Project Control è impegnato nella gestione delle modifiche alla schedulazione piuttosto che all'esecuzione del lavoro programmato. Il "management by exception", che sostanzialmente si concentra sulle varianti al progetto, è il risultato dell'approccio tradizionale. Ma il "miracolo" dell'integrazione di ambito, qualità, budget, costi effettivi e tempi raramente si realizza nei progetti reali, principalmente perché il processo costruttivo non è solo un insieme di attività di conversione, ma anche, ed inoltre, un insieme di flussi interdipendenti della varie partizioni di lavoro e dei cicli

time/cost chart. The forecasted values of time and cost are estimated with simple formulas based on project trends. The method it is suitable for every type of project but actually it is a technical cost-related ICT – based management system used for complex international construction projects.

3. The Production Control approach in construction

A construction project is a temporary production process composed by multiple sub-processes with the aim of creating a building or a civil engineering product. So project control has the aim of monitoring and controlling project progress in relationship with the final goal, while production control has the aim of driving the process or sub process, conceived as a flow of materials, equipment, manpower, work and information, to be conformed to production plan and quality specification (Ballard, 2000). The focus of traditional project schedule control is entirely on delivering project objectives and on the conversion processes defined by activities in the WBS. In addition to this, the traditional approach to project control is more concerned with managing changes to the schedule rather than with execution of scheduled work. The management by exception, meaning to focus basically on project variances, is the result of the traditional approach. But the "miracle" of the integration of scope, quality, budget, actual cost and schedule seldom takes place in real project. This is mainly because the building process is not only a set of conversion activities, but also,

fabbricativi, di risorse, di materiali, e di informazioni. L'approccio del controllo della produzione considera questi aspetti ed altri, come l'aspetto comportamentale delle risorse umane e i processi sociali nelle organizzazioni, per migliorare la prestazione della costruzione.

3.1 Il Last Planner System per il controllo della produzione

Il sistema Last Planner è un approccio orientato alla produzione per la gestione del processo costruttivo introdotto da Ballard (1998, 2000) nell'industria delle costruzioni. Il Last Planner ha l'obiettivo della "Lean Construction" tramite la diminuzione degli sprechi, l'incremento della produttività e la diminuzione degli scostamenti produttivi. Il Last Planner è sostanzialmente basato sul miglioramento dei processi sociali nell'organizzazione di progetto, ovvero ha l'obiettivo di rendere la programmazione un impegno collaborativo e di migliorare l'affidabilità dell'impegno dei membri del progetto (Henrich, Tilley, Koskela, 2005, Koskela, Stratton, Koskenvesa, 2010). Il Last Planner è l'ultimo programmatore del processo, ovvero la persona o il gruppo dell'organizzazione per la realizzazione dell'opera responsabile del controllo delle unità produttive, ovvero il capo cantiere o il preposto o il capo squadra. Quindi il controllo della costruzione si focalizza dal livello del progetto a quello della produzione, e l'oggetto del processo di controllo è il completamento dei compiti fabbricativi individuali o di squadra al livello operativo (Koskela and Ballard, 2006). Di conseguenza il processo di programmazione è suddiviso in quattro livelli gerarchici: il "master schedule", il "phase schedule", il

and even, a group of process flow, i.e. the interdependence of parts in a flow of work, resources, materials, processes and information. The production control approach take into account this and other issues like human resource behaviour and social process, to improve construction project performance.

3.1 The Last Planner System for production control

Last Planner is a production-oriented approach to construction process management introduced by Ballard (1998, 2000) in construction industry. The Last planner aims at achieving the lean goals of decreasing waste, increasing productivity and decreasing variability. The Last Planner approach is mainly based on the improvement of social processes in project organization, i.e. by trying to make planning a collaborative effort and improving the reliability of commitments of team members (Henrich, Tilley, Koskela, 2005, Koskela, Stratton, Koskenvesa, 2010). The Last Planner is the person or organizational construction group accountable for production unit control, i.e. supervisors, foremen and crew bosses. So the focus of construction control shifts from project level to production level, and the object of control process is the completion of individual/crew assignments at the operational level (Koskela and Ballard, 2006). Consequently the planning process employs a four-level hierarchy of schedules: the master schedule, the phase schedule, the look-ahead schedule and the short – term schedule (Koskela, Stratton, Koskenvesa, 2010).

“look-ahead schedule” e il “short-term schedule”.

Il master è il programma complessivo dei lavori e contiene solo le milestones principali. Il phase è la programmazione delle varie fasi di cantiere, il look-ahead contiene le attività principali che devono essere eseguite per completare le fasi di lavoro con una finestra temporale di sei/otto settimane. Il short – term è un programma a livello di compito operativo con l’arco temporale della settimana (Weekly Work Plan, WWP). E’ chiaro che il processo di programmazione può essere efficientemente realizzato solo se basato su sistemi ICT, a causa della complessità insita nei progetti di costruzione e del sistema Last Planner.

L’avanzamento è monitorato su base settimanale, e le cause di non completamento sono analizzate e se possibile rimosse realizzando così il processo di miglioramento continuo. Il Last Planner è un approccio al controllo della produzione che da informazioni riguardo al completamento dei compiti individuali o di squadra ed alle ragioni dei ritardi (Tab. 2). Si tratta in realtà di una riprogrammazione a livello operativo per prevedere la prestazione di progetto a breve termine. L’approccio richiede inoltre lo svolgimento di attività inerenti gli aspetti psico-sociali con l’obiettivo di migliorare la programmazione delle operazioni attraverso il miglioramento comportamentale che comprende pubbliche promesse e pubblici controlli del completamento delle attività e analisi statistiche sulle ragioni dei ritardi.

The master schedule is the overall project schedule and contains major milestones only. The phase schedule divides the master schedule into various work phases aimed to developing more detailed work plan. The look-ahead schedule contains the major activities that must be executed to complete the work phases and has a time window of six/eight weeks. The short-term schedule is an assignment level schedule with a duration of one week (Weekly Work Plan, WWP). It is clear that the planning process can be effective only if ICT – based, due to construction project and control complexity.

The progress is monitored on a weekly basis, and the reason of lack of completion are investigated and are removed if possible to achieve continuous process improvement.

Last Planner System is a production control approach that gives information about the completion of individual / crew assignments and about the causes of variances (table 2).

Really, it is an operational level re-planning to forecast project performance in a short time span. Actually the approach involves the treatment of psycho-social issues aiming to implement the planned task through behavioural means, covering public promises, public checking of task completion and statistics on reasons for non completions.

3.2 La teoria dei vincoli e la catena critica di Goldratt

La teoria dei Vincoli di Goldratt (Theory of Constraints – TOC) e la sua applicazione

3.2 Goldratt’s Critical Chain and the Theory of Constraints

Goldratt’s Theory of Constraints (TOC)

diretta al Project Management, nota come metodo della Catena Critica per la programmazione (Goldratt, Cox 2004, Rand, 2000, Henrich, Tilley and Koskela 2005), è orientata al processo di controllo sia a livello di progetto che a livello di produzione. La Catena Critica si focalizza sui vincoli della produzione che impediscono il raggiungimento dei suoi obiettivi. Anche Goldratt (2004) individua tra le principali ragioni degli scostamenti della programmazione alcuni aspetti psico-sociali, comportamenti tipici dei responsabili della produzione e del progetto. Il concetto fondamentale della programmazione con il metodo della catena critica è che la catena critica delle attività, svolte dalle risorse chiave, è protetta dai ritardi con dei buffer temporali. Le durate delle attività vengono ridotte, e i buffer temporali che costituiscono i margini di sicurezza vengono aggiunti alla fine del progetto o dei percorsi nei sub-reticoli. L'esecuzione del progetto è diretta con la tecnica del buffer management. Sino a quando rimane una parte predeterminata di buffer inutilizzata si presuppone che tutto proceda regolarmente, altrimenti occorre intraprendere delle azioni correttive. In realtà il concetto base della programmazione con la Catena Critica è l'ottimizzazione del flusso di lavoro attraverso il progetto (fig. 5). Il metodo della catena critica ha l'obiettivo principale di migliorare il processo di programmazione e controllo tramite le tecniche ICT di tipo reticolare. Fondamentalmente si tratta di uno strumento di programmazione che, oltre alle consuete informazioni sul progetto fornisce i dati sul consumo dei buffer, permettendo di dare delle priorità per le azioni correttive sulle attività da svolgere successivamente. Quindi la misura della prestazione dello stato del progetto è realizzata con questo set di dati ed i relativi KPIs (tab. 2).

and its direct application to Project Management, known as Critical Chain Scheduling (Goldratt, Cox 2004, Rand, 2000, Henrich, Tilley and Koskela 2005) addresses both project oriented and production oriented control processes. Critical Chain focuses on the constraints of a project production which prevent achieving its goals. Also Goldratt (2004) argues that principal reason for project overrun are certain typical human behavior patterns. Main concept of critical chain scheduling is that the critical chain of activities, performed by key resources, is protected from time overruns with buffers. Activity durations are reduced and safety buffers of time are added at the end of the project or sub-network paths. The execution of the project is managed through the use of buffer management. Since there is some predetermined part of buffer remaining unused, everything is assumed to go well, otherwise a corrective action must be taken. Actually core concept of critical chain scheduling is the optimization of work flow through the project (figure 5).

The critical chain method has the main objective of improving project planning and control process with ICT – based networking techniques.

Basically it is a network based planning tool that gives controllers usual information of activity networks models. But, in addition to this, the Critical Chain gives information about buffer consumption, thus allowing to give a relative priority in upcoming activities for corrective actions. So performance measurement of project status is performed with this set of data and inherent KPIs (table 2).

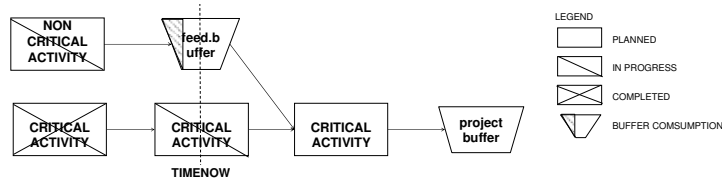


Figure 5: Critical Chain Scheduling: feeding buffer and project buffer.

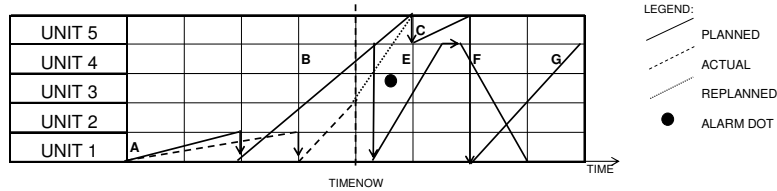


Figure 6: Location Based Management System: project/process control

3.3 Il Sistema di Pianificazione e Controllo basato sulla Localizzazione delle attività

Come osservato precedentemente, la modellazione del processo costruttivo necessita di un maggiore dettaglio per quanto riguarda il flusso delle risorse attraverso le attività di progetto. Nella tecnica di programmazione basata sulla localizzazione delle attività, Location-Based Management System (LBMS), le fasi di lavoro formate da attività ripetitive svolte dalle medesime risorse, sono rappresentate su di un diagramma tempo / spazio che utilizza i principi generali del metodo Line Of Balance (LOB) / Flow-line (Kenley, Seppanen, 2010).

Viene inoltre definita, con l'impiego di un reticolo per attività elementari, una logica strutturata tra le diverse fasi e le attività, permettendo la programmazione del progetto con un algoritmo di tipo PDM (fig. 6). Si tratta di un processo di programmazione e controllo orientato alla produzione. Il sistema di controllo basato sulle localizzazioni

3.3 Location – Based Planning and Controlling System

As previously discussed, construction process modeling, for repetitive projects in particular, needs a more detailed model regarding resource flows through project activities. In Location Based Management System (LBMS) working tasks, set of repetitive activities performed by the same resources, are plotted on time / space chart using general principles of the Line of Balance (LOB) / Flow-line (Kenley, Seppanen, 2010).

In addition to this a layered logic between tasks and activities is set on a networking technique basis, thus allowing project scheduling with a PDM - based algorithm (figure 6).

It is a production oriented schedule and control process. Location Based Control system uses locations to generate on – time response by management through visualisation of any problems before

genera risposte tempestive della direzione attraverso la visualizzazione dei possibili problemi futuri con la creazione di segnali di attenzione, cosiddetti allarmi (Alarm). In particolare un allarme è generato fondamentalmente se si prevede che un predecessore ritarderà un successore (Kenley, Seppanen, 2009 and 2010). Il Location – Based Scheduling è uno strumento di programmazione e controllo che da sia le informazioni del LOB che del PDM, oltre ai segnali di allarme. Quindi la misura della prestazione dello stato del progetto è realizzata con questo set di dati ed i relativi KPIs (tab. 2). Per la sua struttura basata su più strumenti del tipo ICT si tratta di un modello adatto a progetti di costruzione complessi (fig. 6).

4. Discussione

Il presente lavoro ha analizzato vari metodi di controllo dei progetti di costruzione basati sulle tecniche ICT e i loro principi per la comprensione dello stato del progetto. I metodi sono stati classificati in approcci tradizionali, orientati al progetto, e approcci innovativi, orientati alla produzione (tab.1 e 2).

Fondamentalmente gli approcci tradizionali analizzati per il project control sono soluzioni molto generiche ma hanno il merito di aver fornito una solida base per le soluzioni necessarie alle diverse applicazioni tecniche e industriali ed i rispettivi progetti. Il metodi nei quali le caratteristiche della produzione per la costruzione sono meglio focalizzate (l'approccio del controllo della Produzione) sono più adatti all'industria delle costruzioni e quelli analizzati rappresentano quelli più significativi.

they happen with the generation of warning signals called Alarms. In particular the Alarm is generated basically if the forecast of a predecessor delays the forecast of a successor (Kenley, Seppanen, 2009 and 2010). The Location-Based Scheduling is a planning and controlling tool that gives controllers the usual information of LOB and PDM, adding warning signals (table 1). So performance measurement of project status is performed with this set of data and inherent KPIs (table 2). Due to the scheduling ICT tools the model it is suitable for complex construction projects (figure 6).

4. Discussion

This paper has reviewed various construction project control ICT – based methods and their principles for understanding the status of project. The control methods have been categorized into traditional approaches, project oriented, and innovative approaches production oriented (table 1-2).

Basically the reviewed traditional project control approaches are very generic solutions. Therefore they have provided sound starting points for solutions for wide range of different types of disciplines and their projects. The methods where the characteristics of construction production are in focus (Production Control approach) are much more specific for construction, and the reviewed methods represent the ones that have particularly significance.

<i>Control method</i>	<i>Tools</i>	<i>Control data</i>	<i>KPIs</i>
Traditional Construction Control approach			
Time oriented	<ul style="list-style-type: none"> Barchart; 	Activity list; Activity dates and duration Milestones Percentage of completion of activities	Project Time consumption Project percentage of completion
	<ul style="list-style-type: none"> Activity Network (PDM); 	Activity list; Activity dates and duration Milestones Percentage of completion of activities Construction logic Floats consumption	Project Time consumption Project percentage of completion Critical activities to complete Out of sequence progress
	<ul style="list-style-type: none"> Line of Balance / Flow-line 	Activity list; Activity dates and duration Milestones Percentage of completion of activities Activity location Time/space conflicts Resource productivity	Project Time consumption Project percentage of completion Completed project locations Resource efficiency
Time/cost oriented	<ul style="list-style-type: none"> Earned Value Method (EVM) 	Activity list; Activity dates and duration Percentage of completion of activities Activity cost	Project Time consumption Project percentage of completion CPI /SPI Project Performance Index

Table 1. Construction project-oriented control methods

Control method	Tools	Control data	KPIs
<i>Innovative Production Control approach</i>			
The Last Planner System	<ul style="list-style-type: none"> • Barchart; • Weekly Work Plan (WWP) 	Assignment list; Assignment dates and duration Milestones Percentage of completion of Assignments Analysis of non completed assignments Prerequisites for assignments	Project Time consumption Project percentage of completion Process variances
Critical Chain / Theory of Constraints	<ul style="list-style-type: none"> • Activity Network (PDM); 	Activity list; Activity dates and duration Milestones Percentage of completion of activities Construction logic Analysis of project constraints Buffer consumption	Project Time consumption Project percentage of completion Process variances Buffer consumption Critical chain progress
Location – Based Planning and Controlling System	<ul style="list-style-type: none"> • Activity Network (PDM); • Line of Balance / Flow-line 	Activity list; Activity dates and duration Milestones Percentage of completion of activities Layered logic Activity location Resource productivity	Project Time consumption Project percentage of completion Completed project locations Resource efficiency Out of sequence progress Process warnings

Table 2. Construction production-oriented control methods

I metodi di project control orientati alla produzione hanno indubbiamente il merito di aver fornito una nuova dimensione per comprendere meglio la gestione del processo costruttivo (Kahkonen, 1994). In particolare si citano gli aspetti relativi al movimento delle risorse, alla ri-lavorazione e all'analisi dei guasti e dei ritardi, agli aspetti comportamentali e alla pianificazione condivisa ai vari livelli.

5. Conclusioni e future linee di ricerca

L'analisi dei metodi per il controllo della costruzione presenti nella letteratura internazionale, sia orientati al progetto come il diagramma a barre, il PDM e l'EVM, o orientati alla produzione come il Last Planner, la Catena Critica e il LBMS, mostra una forte necessità di un maggior approfondimento e di ricerca futura. E' infatti chiaro che i due approcci, tradizionale e innovativo, sono effettivamente complementari e la maggior parte dei metodi che sono stati presentati coprono aspetti differenti che completano la visione della costruzione da differenti punti di vista. E' chiaro come il "Lean Thinking" abbia fortemente influenzato lo sviluppo dei metodi di controllo orientati alla produzione. Infatti la "Lean Construction" ha l'obiettivo di dare più valore al cliente finale con il miglioramento del controllo dei processi costruttivi, fondamentalmente attraverso la riduzione degli sprechi (*muda*), la responsabilizzazione degli operatori ed il miglioramento continuo (*kaizen*). Quindi sino a quando le tecniche di programmazione non saranno in grado di modellare il flusso dei processi, esse porteranno a scarsi risultati sia nella gestione che nella riduzione degli sprechi.

Il Construction Control necessita dunque di

The production oriented project control methods have successfully presented important additional dimensions for understanding and managing performance of construction (Kahkonen, 1994). Examples of those are resource movement, re-work and failures, delay analysis, behavioural issues and co-planning.

5. Conclusion and future research

The overview of construction control methods from literature, either project oriented like barchart, PDM and EVM, or production oriented like Last Planner, CC and LBMS, actually leads to the need of a major investigation and future research. In fact the two approaches, traditional and innovative, are really complementary and most of the methods that were presented cover different issues that complete the view of construction from different standing points.

Lean Thinking was really the engine of the development of the new production oriented control methods.

In fact Lean Construction has the goal of giving more value to the final client through building processes control improvement, basically focusing on waste reduction (*muda*), on making operators more responsible for work assignments, and on processes continuous improvement (*kaizen*). As a matter of fact until planning techniques will not model process flows properly they will lead to poor planning management or waste improvement.

Construction control needs an integrated

un approccio integrato che deve essere ancora sviluppato. Per approccio integrato si intende un metodo di controllo che legghi insieme i seguenti aspetti: i) il progetto/processo di costruzione come sistema; ii) l'aggiornamento e l'accesso ai dati di monitoraggio in modo semplice e immediato; iii) il supporto per il controllo del progetto per i vari partner di progetto.

E' chiaro inoltre che tutti questi strumenti possono essere efficientemente impiegati solo se realizzati tramite applicazioni computerizzate, ovvero sono tutti basati sull'Information and Communication Technology (ICT).

Lo sviluppo di un metodo che meglio si adatti alle caratteristiche delle moderne operazioni costruttive è la strada verso l'innovazione nel project control per la costruzione.

approach that is still to be developed. By this integrated approach we mean a control method that is tying together viewpoints such as i) Construction project as a system and its parts, ii) Continuous updating and access to project monitoring and control data in an easy manner, iii) Support for multi-partner project control.

It is also clear that all of these tools can be effectively implemented only if they are realized with a computer application, ie they must be ICT - based.

The development of methods that are capturing characteristics of modern construction operations are the way towards this kind of solutions.

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II

Quality Evaluation of Construction Activities for Project Control

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Quality Evaluation of Construction Activities for Project Control

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Abstract-The measurement of the performance of a construction project is a fundamental task of Construction Management. This is usually based on professional observations or use of metrics such as Key Performance Indicators (KPIs), that are intended to represent the health of the construction project and can be used to predict the future project performance.

This paper presents a research effort on the way forward to implement quality related metrics for construction project control. The Quality Breakdown Structure is adopted as basic tool to consider the various elements of construction quality like product quality and process quality, to put them into relationship and to evaluate their relative weight in the construction project and its sub-processes.

The proposed quality related performance indicators can be loaded to the construction project scheduling model, with the goal of showing to Project Manager and to Stakeholders the achieved versus planned quality in the project status. This could improve construction project control process, with the aim of the timely implementation of corrective actions to achieve project success.

Keywords- Construction; Project Control; Quality; Project Management; Construction Performance

I. INTRODUCTION: PROJECT MANAGEMENT METRICS AND KPIS IN CONSTRUCTION

Nowadays the construction project management needs much more meaningful information than in the past. In fact several driving forces have improved the need for information in construction projects:

- construction projects we are working now are made of more sub-processes than in the past, thus improving project complexity;
- construction project total duration is always increasing;
- economical and financial efforts for stakeholders are increasing;
- as technology increases its complexity, time and cost requirements are becoming more and more difficult to satisfy;
- complex construction projects need well organised management with detailed and up to date information.

All of these driving forces and the market performance problems make the need for meaningful information of capital importance to achieve project success^[1]. In fact project success can be achieved only with the support of an integrated Project Reporting System, based upon a specific Project Measurement System that has the task of monitoring project performance with a metric system to allow Project Managers to implement timely and proper management actions to meet project objectives, milestones and deliverables. So project metrics should be reported in a timely manner (with the goal of having real time data), should be oriented at the adherence of the competing constraints (i.e. time, cost, quality, etc.) and must be used to implement corrective actions to maintain baselines. Project metrics can include: time, cost, scope, quality, customer satisfaction with project performance, safety, risk mitigation and many others like: continuous improvement; benchmarking; accuracy of the estimates; accuracy of the measurements; accuracy of the targets for the metrics. In addition to this Project management process metrics have to be directly related to lessons learned and best practices, and is directed to stakeholders, working levels and management^[2].

The measurement problem in construction projects is a well-known project management issue. Metrics in project management are a measurement of project performance, but not all metrics are equal in importance. Reference [2] divides project measurement into “normal” metrics and Key Performance Indicators (KPIs). Key Performance Indicators are those critical metrics that can define in a concise and proper way the project status and can be used to forecast the future project performance. The KPIs are the information needed by project team and stakeholders for decision making.

Reference [3] defines three categories of metrics:

- Results Indicators (RIs), give information about what has been accomplished;

- Performance Indicators (PIs), give information about what must be done to increase or meet performance requirements;
- Key Performance Indicators (KPIs), the critical performance indicators that can drastically increase performance or accomplishment of the objectives.

In Project Management Practice there are several metrics that can be identified for project measurement, but while decades of metrics can be defined, only few of them can be used as KPIs. In construction project management there are some measures of building products and processes quality that are mandatory by law and some other ones that are requested by owner/customer through contract documents and specifications. Traditionally the performance of construction projects is measured by means of three performance indicators: cost, time and quality. Recent research employed additional performance indicators to better evaluate construction projects. In particular the Minister of Construction of the United Kingdom ^[4] identified six KPIs: cost, time, quality, health and safety, business performance and change orders. Instead, updated research ^[5], added to time, cost, quality, and safety KPIs, the following KPIs: environment impact, client and project team satisfaction, and technology transfer.

Reference [2] reported the following KPIs for the case studies of Disneyland and Disney World: time, cost, scope, safety, aesthetic value and quality, with the last three being fixed values that could not be negotiated. Reference [6] for pharmaceutical construction projects included only the following KPIs: cost, time, quality, safety and design/space efficiency. While all of the described KPIs are of greater interest in Construction Management, it is believed that the quality KPIs are the most important ones, and so the present paper focuses on the development of quality KPIs.

II. RESEARCH METHODOLOGY

The aim of the paper is the definition of quality – related KPIs for a construction project for project control purposes. Indeed quality assessment for a construction project is a very difficult task for both Project Managers and Stakeholders due to project complexity, in fact construction involves a lot of different trades and needs many professional specializations. Thus technology oriented quality assessment can be an interesting point of view to limit the boundaries of the problem.

Assuming that for a public housing construction project there are at least more than an hundred types of different activities that have to be related to the dimension of the building, the problem of quality assessment of each activity can be overwhelming. In fact each activity quality is defined by the satisfaction of a number of requirements set by national or local laws and regulations and / or set by the project contract, documents and specifications.

The solution can be searched in activity sampling for tests and in weighting each activity quality to a percentage of the overall project quality to be able to sum up the different types of quality performance.

As Project quality is made of two main parts, product quality and process quality, it is important that both are taken into account for the project quality assessment. Only in this way construction quality assessment will be related to total quality assessment. This quality assessment methodology could be a good estimate of the overall project quality but it is not really building and construction process quality. It is only one of the various Project Performance Indicators to measure project performance.

The study of previous literature about construction quality estimate and construction project metrics has allowed benchmarking and analysing existing approaches to construction project quality evaluation, highlighting positive and negative issues of each approach. The research is also based on two real construction projects that have been described from the quality standing point in recent studies performed at the University of Bologna ^[7,8].

The main task of the research is the definition of a method to assess project quality performance through the as – of date for project control purposes. Note that the quality assessment performed with the proposed method is an evaluation of total quality project performance which can be used also for contract purposes, but it is not meant to be a quality certification of the building or construction project.

The research is developed into three phases. In the first phase literature about project metrics and construction projects performance measurement is reviewed. In particular existing and proposed project quality KPIs computation methods are focused.

In the second phase the activity quality performance quantification problem is tackled. First it is needed to specify activities of the construction project through a Quality Breakdown Structure (QBS) that identifies work packages that group activities with similar quality specifications. The Work Packages (WPs) of the QBS are the smaller groups of activities which have the same quality specification. Than the proposed method for quality KPI estimation evaluate the quality performance of Work Packages related to two groups of requirements: product or sub-products related requirements and process or sub – processes related requirements. The selection of the most important requirements between these two groups allows defining WP quality items that compose WP quality and thus allowing quality measurement and aggregation by a weighting system.

This weighting system is the core process of quality KPIs computation. The QBS allows identifying the quality control

points of the construction project (Figs. 1 and 2).

PROJECT QUALITY PERFORMANCE	A _i	WORK PACKAGE (I) QUALITY PERFORMANCE	B _{i,j}	WORK PACKAGE QUALITY ITEM (J)
1 HOUSING CONSTRUCTION PROJECT	A1	1.01 BUILDING SITE ORGANISATION	B1,1	1.01.01 BUILDING SITE LAYOUT
			B1,2	1.01.02 FENCE/SIGNALS
			B1,3	1.01.03 ELECTRICAL PLANT
			B1,4	1.01.04 SCAFFOLDS/FALL PR.
			B1,5	1.01.05 TOWER CRANE
	A2	1.02 REINFORCED CONCRETE	B2,1	1.02.01 CONCRETE QUALITY
			B2,2	1.02.02 FINISHED CONCRETE
			B2,3	1.02.03 REBAR
			B2,4	1.02.04 FORMWORK
			B3,1	1.03.01 BEAM/WALL JOINT
	A3	1.03 WOODEN FLOOR CONSTRUCTION	B3,2	1.03.02 FLOOR WOODEN STR.
			B3,3	1.03.03 WOOD QUALITY
			B4,1	1.04.01 BEAM/WALL JOINT
	A4	1.04 WOODEN ROOF CONSTRUCTION	B4,2	1.04.02 ROOF WOODEN STR.
			B4,3	1.04.03 WOOD QUALITY

Fig. 1 Sample Quality Breakdown Structure for the example project

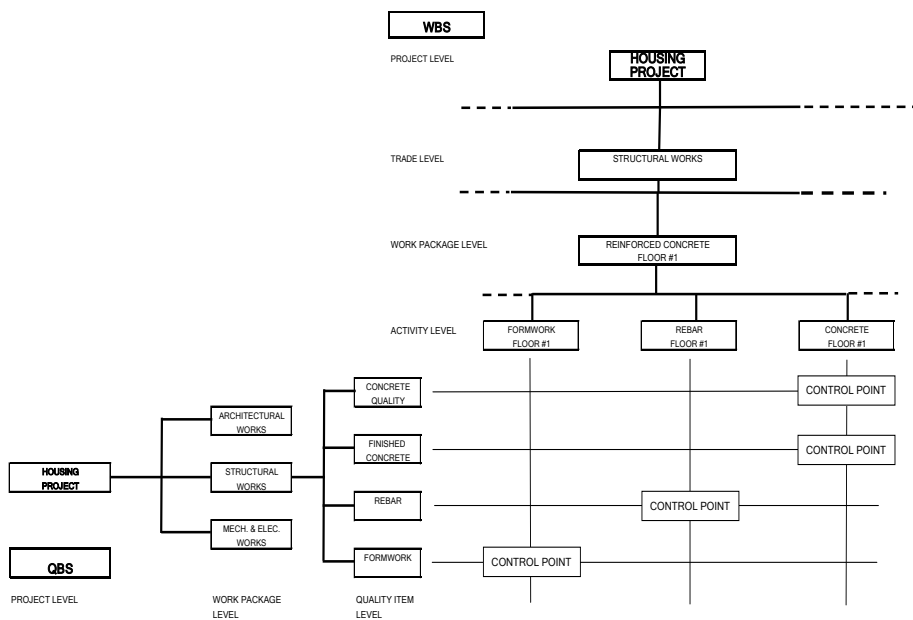


Fig. 2 Matrix relation between QBS and WBS elements

In the third phase overall project quality assessment through the as-of date is performed. This is allowed by quality weighting of the WP of the QBS. The weighting system at the project scale is realised taking into account economic, aesthetic or functional aspects of the specific construction project. Then by adding the weighted WP performance of each WP accomplished at the as-of date, the quality project status can be evaluated at each time-now or on a real time basis.

III. APPROACHES TO QUALITY KPI EVALUATION IN CONSTRUCTION

In construction projects the measure of quality performance is a complex task as, in general, construction project are complex projects^[9]. While for time and cost it is easy to define some quantitative indexes to measure time and cost performance and so define easily some relevant KPIs, it is much more difficult to quantify and measure quality performance of a construction project and develop related to quality meaningful KPIs.

Indeed quality is basically technology related and the metrics of quality must be specific for each kind of project. For construction, few are the methods and approaches aiming at an overall project quality assessment that can quantify a quality KPI. This section intends to provide a review of three important approaches to quality KPIs development (Table 1). The three approaches were selected because of their relevance and their presentation in prestigious international scientific journals.

TABLE I DIFFERENT APPROACHES TO CONSTRUCTION PROJECT QUALITY MEASUREMENT

	Project quality KPIs approach	Criteria	Quality Breakdown Structure (QBS)	Quality type	Quality Metric
1	The KPIs Working Group ^[4]	Number of Defects/Quality issues	No (list of Quality Issues)	Product Quality	Score 1 - 10
2	Building and Construction Authority – “conquas” ^[10]	Quality indicators for standard Work Packages weighted with CONQUAS criteria	Yes, but standardized QBS for each building category	Product Quality	Percentage quality index
3	El-Rayes and Kandil ^{[11][12]}	Quality indicators for each activity with relative percentage weight	Yes, specific for the single project	Product Quality	Percentage quality index
4	Present Paper	Quality indicators for each Work Package with scoring system	Yes, specific for the single project	Product and Process Quality	Percentage quality index

The first approach^[4] defines the quality KPIs basically as the frequency of defects in the end product. In fact the KPIs Working Group of the Minister of Construction of the United Kingdom assumes that quality in construction is subjective and means different things to different process operators, and that there is no objective recognised method of measuring quality in construction industry. So the aim of the quality KPIs is to improve the visibility of quality issues on construction projects through the measurement of “Quality Issues”. A “Quality Issue” is defined as an issue that affects the project so that work needs to redone, modified or compromised to a lower standard than originally agreed. Therefore the KPIs measure construction quality recording all quality issues on all elements within the project from project commencement. At the operational level the KPI for quality is the number of quality issue, while at the project / headline level the Quality KPI is called Defects KPI and it is recorded using a scoring system with the score 10 for a product/element apparently defect free and a score 1 for a totally defective product. It is worth mentioning that in this approach there is another quality – related index which is Client Satisfaction, divided in four subcategories each with a score from 1 to 10. In fact, from a Total Quality Management standing point Client Satisfaction is an important quality-related element. This approach measures how satisfied is the client with the finished products, and with the service of the contractors using the score against the 1 to 10 scale, with 10 meaning totally satisfied, 5/6 neither satisfied nor dissatisfied and 1 totally dissatisfied. At the operational level the KPI measures how satisfied is the client with certain client - specified criteria, using the score against the 1 to 10 scale, but weighted together to determine their level of importance.

The second approach is the one of the Construction Industry Development Board of Singapore that developed an objective quality measurement System for building construction called CONQUAS, which is now also used as a quality standard for ISO 9000 local enterprises quality certification^[10].

The CONQUAS system indicates criteria for measuring construction quality and determines to what extent a project satisfies those requirements, related to a representative sampling of the building. Quality metric is based upon a scoring system that considers Building Quality divided into three primary component areas: Structural works, Architectural works and Mechanical and Electrical works. The weight system is a compromise between the cost proportion of the three components and their aesthetic value, related to the following building categories:

- Category A/B: commercials, industrial, institutions etc. (A: with central cooling system; B: without central cooling system);
- Category B: private housing;
- Category C: public housing;
- Category D: landed housing (bungalows, semidetached houses, terrace houses etc.).

The procedure to find the construction project quality index starts with the computing of the percent passing the inspection points, depending on sample inspections. This value is combined with other elements in the same component (e.g. formwork and rebar in structural works). The component total (e.g. structural) is weighted a second time based on the building category. The sum of the three component scores is used as the final building score, i.e. the quality index.

The third approach to quality index evaluation is the one used by El Rayes and Kandil in recent studies for highway

construction, in order to facilitate the measurement and quantification of construction quality^[11, 12]. The approach is a development of the “Quality – Based Performance Rating System” of the American National Cooperative Highway Research Program (NCHRP) for contractors qualification^[13, 14].

The method identifies a number of measurable quality indicators for each activity of the construction project. The indicators are derived from performance based models that correlate the long term performance of the end product of each activity to its quality indicators. Quality indicators are also selected with the aim of allowing practical and objective measurement of performance. Then the quality of each activity of the construction project is estimated on quality indicators basis.

A weighted approach is used to aggregate the estimated quality for all the considered activities to provide an overall quality of the project level. For each activity of the Work Breakdown Structure (WBS) two types of weights are identified: the weight (B_{ij}) of each quality indicator of the activity to indicate the relative importance of each indicator to the others being used to measure the quality of the activity and the weight (A_i) of the activity to represent the importance and contribution of the quality of the single activity to the overall quality of the construction project.

$$Q = \sum_{i=1}^n A_i \sum_{j=1}^k B_{ij} \times Q_{ij} \quad (1)$$

where Q = overall quality of construction project; A_i = weight of quality of activity (i) compared to other activity in the project; B_{ij} = weight of quality indicator (j) of activity (i), compared to other indicators in activity (i); Q_{ij} = performance of quality indicator (j) in activity (i); n = number of activities of the construction project; k = numbers of quality indicators of activity (i).

The model of Equation (1) allows measuring and quantifying the overall quality of the construction project with a practical and empirical approach.

The three different approaches are synthesized in Table 1.

IV. QUALITY EVALUATION OF CONSTRUCTION ACTIVITIES AND PROJECT QUALITY BREAKDOWN STRUCTURE (QBS)

Quality KPI definition for a construction project is developed through a method defined by the integration of the three approaches previously described. The proposed operational procedure is applied to a simple example project of refitting of two buildings of a public institution^[7, 8].

Core tool of Project Management is the Work Breakdown Structure (WBS) that is the structure of the project information integration system^[15-18]. Work Breakdown Structure is a key element of traditional project control. The Work Breakdown Structure is a deliverable-oriented hierarchical decomposition of the work to be executed into work packages that organizes and defines the total scope of the project^[19]. The WBS is meant to provide an integrated framework for time, cost and quality control of working packages, but the WBS approach to project control is not easy to develop successfully. So to ensure efficient quality oriented control processes it is needed a Quality Breakdown Structure (QBS)^[12]. The QBS is a hierarchical decomposition of the construction project into Work Packages (WP) that groups the activities which have the same quality requirements and specifications. A sample of the QBS for the example project is presented in Figure 1.

Work Packages are also groups of activities that satisfy the requirement of time/cost/quality integration for control purposes and are the smallest element to be under control. Work Packages often correspond to contract packages or to pay items of a contract. The quality of every single WP of the QBS contributes to the overall quality of the construction project. The Work Package contributing to project quality is quantified through a weighting system that is set for the specific project taking into consideration economic and aesthetic or functional issues. In Figure 1 the weight for activity (i) is A_i .

For Quality control purposes the Work Package quality is evaluated as a weighted sum of the actual value of each quality item of a work package. The weighting process is performed with a scoring system that weights each quality index related to final WP quality. In fact, as a matter of facts, building quality operators usually are not able to evaluate the relative weight of an item related to the other items, but they can evaluate very well the weight / importance of a quality item related to the overall work package quality. So the technological quality of a quality item is quantified with a score, called Quality Index, from 1 to 10, where 1 means no effect at all on final quality and 10 is a direct strong influence of the quality of the item on the final quality of the work package.

The smaller the Work Packages are, the more flexible and accurate the control will be. As the C/CSC guide and updated research states^[15, 16], the control (cost) account level is the WP level, the lowest level in which functional responsibility for individual WBS element exists, where cost are accumulated and performance measurement is performed. The relation between the Quality Breakdown Structure (QBS) and the WBS assigns product and process quality requirements to appropriate group of activities of a Work Package. This relationship may be visualized as a matrix with the quality elements of the QBS listed in one axis and the applicable WBS elements listed in the other. The intersection between these two elements of the matrix is the quality control points, if applicable (Figure 2). The PMBOK^[19] defines the control point as the point of the WBS in which the

integration of scope, budget, actual cost, and schedule takes place, and where the measurement of project performance will occur, even on a quality basis. So the Quality Breakdown Structure (QBS) of a construction project enables the objective evaluation of the overall construction quality through quality items measurement. The development of a QBS for a construction project provides the capability of estimating the overall construction quality performance at both the activity and the project levels being in relation to the WBS (Fig. 1 and Fig. 2).

Quality estimate of a construction activity is performed through quality indexes evaluation of each quality item defined for the Work Package of the QBS that include the activity. The definition of quality items for each WP is developed by means of the ISO 9001 Quality Plan for the specific construction project. Table 2 shows quality items for the example of the reinforced concrete Work Package. Quality items should be quantifiable or measurable and are related to both product quality and process quality. Product quality items are related to quality performance of the finished product or sub-product of the activity, while process quality items are related to quality performance of production sub-process of the activity, i.e. operation procedures for quality or safety, e.g. concrete vibration, bricks wetting before placing or fall protection devices for bricklayers. In Table 2 the finished concrete quality item is comprehensive of concrete vibration and cast in place. Table 3 shows the building site organisation WP which has only process related quality items. The quality items of each WP are weighted with a score ($B_{i,j}$) from 1 to 10, where a weight of 10 means the maximum estimated effect of the quality item on the overall quality of the activity. As previously said experience shows that quality supervisors are not able to weight the single items between each other and set a percentage of contribution to the work package quality as it is done at the project level, but they can mark the influence of the good quality of the item to the overall quality of the Work Package with a score meaning to what extent good or poor quality of the item causes good or poor quality of the WP itself. The weight is also evaluated in relation to relevant building law and regulations, and in relation to project documents and specification^[8].

TABLE II SAMPLE PROJECT: REINFORCED CONCRETE WORK PACKAGE QUALITY EVALUATION (QI), PRODUCT AND PROCESS QUALITY

WORK PACKAGE: Structural work: reinforced concrete

j	Quality item (j)	Weight of item ($B_{i,j}$)	Quality Index ($Q_{i,j}$)	Quality Index weighted ($Q_{wi,j}$)	Work Package Quality Performance (Q_i)
1	Concrete Quality	10	100%	10	
2	Finished Concrete	8	80%	6,4	
3	Rebar	8	95%	7,6	
4	Formwork	7	80%	5,6	
	Total	33		29,6	90%

TABLE III SAMPLE PROJECT: BUILDING SITE ORGANISATION WORK PACKAGE QUALITY EVALUATION (QI), PROCESS QUALITY

WORK PACKAGE: Building Site Organisation

j	Quality item (j)	Weight of item ($B_{i,j}$)	Quality Index ($Q_{i,j}$)	Quality Index weighted ($Q_{wi,j}$)	Work Package Quality Performance (Q_i)
1	Building Site layout	8	80%	6,4	
2	Fence/Safety Signals	8	75%	6	
3	Building Site electrical plant	10	90%	9	
4	Scaffolds/fall protection	10	95%	9,5	
5	Tower Crane installation	10	90%	9	
	Total	46		39,9	87%

The quality index (Q_{ij}) for the quality item (j) of the work pack (i) is evaluated with two alternative methods:

- the percentage calculated with the ratio of the number of positive tests and the total number of tests executed meeting project quality specifications;
- the percentage of adherence to specification estimated by the quality control function.

The actual quality performance is recorded before corrective actions implementation and/or reworking of the defective element.

Then the quality index weighted ($Q_{wi,j}$) is calculated with the following Equation (2):

$$Q_{wi,j} = B_{i,j} \times Q_{i,j} \quad (2)$$

where $Q_{wi,j}$ = Quality index weighted, of the item (j) of the WP (i); $B_{i,j}$ = weight of the quality item (j) on the overall quality of the WP (i); $Q_{i,j}$ = Quality index (j) of the WP (i).

The Quality Performance of the Work Package (Q_i) is estimated as the percentage of satisfaction of the requirements of the quality index with their weights, estimated as the sum of the actual quality index weighted with the following Equation (3).

$$Q_i = \frac{\sum_j^k Q_{wi,j}}{\sum_j^k B_{i,j}} \times 100 \quad (3)$$

where Q_i = Quality Performance of the WP (i); $Q_{wi,j}$ = Quality index weighted of the item (j) of the WP (i); $B_{i,j}$ = weight of the quality item (j) on the overall quality of the WP (i); k = number of quality items (j) of WP (i); (e.g. Tables 2 and 3).

V. QUALITY KPI FOR CONSTRUCTION PROJECT: DEVELOPMENT AND SAMPLE APPLICATION

The Quality KPI, representing the overall quality of the Construction Project, is estimated as the sum of the quality of each Work Package of the project weighted to represent the importance and contribution of the quality of every Work Package to the overall quality of the project.

As previously said the weight of each Work Ppackage is evaluated with a compromise between the cost proportion and aesthetic and functional consideration, and it is specific for the single construction project.

The evaluation of the quality KPI is a dynamic procedure of project control that estimates at each time-now and at the end of the Project the adherence of construction processes and products with project quality specifications. At each as-of date (t) and at the project completion the quality KPI can be estimated with the Equation (4).

$$Q(t) = \sum_{i=1}^n A_i \times Q_i \quad (4)$$

where $Q(t)$ = estimated quality KPI of the construction project through the as of date (t); A_i = relative weight of the quality of Work Package (i) to the overall project quality; Q_i = quality performance of Work Package (i); n = number of Work Packages (i) of the construction project.

Table 3 shows relative weights of the activities of the sample project.

If, corrective actions to improve project quality are implemented after the quality assessment at the as-of date (t), then the quality KPI should be updated to be adherent to real project status.

By loading quality performance to project schedule it is possible to assess quality performance of the construction project through the as-of date, so the reporting system of the project status can also cover quality information. Table 4 shows project sample Quality KPI (Q) evaluation for the reporting system at project completion.

TABLE IV SAMPLE PROJECT: CONSTRUCTION QUALITY KPI (Q) AT PROJECT COMPLETION

PROJECT QUALITY KPI (Q)	WP WEIGHT (A _i)	WORK PACKAGE DESCRIPTION	WORK PACKAGE QUALITY PERFORMANCE (Q _i)
	3,0%	BUILDING SITE ORGANISATION	87%
	5,0%	REINFORCED CONCRETE	90%
	5,0%	WOODEN FLOOR CONSTRUCTION	90%
	15,0%	WOODEN ROOF CONSTRUCTION	90%
	2,5%	EXTERNAL WALL	85%
	2,0%	INTERNAL WALL	85%
	3,0%	ROOF COVERING	88%
	4,0%	PLASTER FINISH	90%
	7,0%	FLOORS AND WALLS TILED FINISH	90%
	2,0%	PAINTINGS	93%
	17,0%	PLUMBING AND SANITARY WORK	85%
	10,0%	ELECTRICAL WORKS	92%
	2,0%	THERMAL AND SOUND INSULATION	90%
	3,0%	SITE IMPROVMENTS	88%
	2,0%	DEMOLITION	77%
	17,0%	DOORS AND WINDOWS	94%
	0,5%	EARTHWORKS	90%
89,4%	100,0%		

VI. CONCLUSIONS

Project performance measures like KPIs are of paramount importance for Project Managers and Stakeholders in Project Control. In construction projects time and cost related KPIs are well known indexes to assess project status, but because of construction project complexity quality-related KPIs are of difficult evaluation.

The basic tool for construction project overall quality estimate proposed is the Quality Breakdown Structure which is composed of different quality related Work Packages. The quality KPIs of each WP can be easily estimated by project control team and with the QBS hierarchical structuring it is possible to estimate overall project quality and the related Quality KPI.

The overall quality performance assessment approach described is an efficient method that views project quality performance as a weighted sum of quality performance of the Work Packages of the whole construction project. Quality

performance of single Work Package is estimated as a weighted sum of quality indexes related to performances of each quality item component of the Work Package.

The found Quality KPI is dependent on the technology – related quality of individual activities, i.e. construction elements, but really the overall quality of a building is not a simple sum of the quality of subparts but it depends also on the relation – quality between subparts, and it is the synthesis of all of these contributions that develops the building quality concept. This is the way forward to Quality KPIs estimation of future research.

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III

Repnet: Project Scheduling and Workflow Optimization for Construction Projects

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REPNET: project scheduling and workflow optimization for Construction Projects

REPNET: ottimizzazione della programmazione dei lavori per i progetti di costruzione

Project planning and control are core processes for construction management. In practice project planning is achieved by network - based techniques like Precedence Diagramming Method (PDM). Indeed many researchers and practitioners claims that networking techniques as such do not provide a suitable model for construction projects. Construction process modeling should incorporate for specific features of resource flows through project activities. So an improved resource scheduling method for construction is developed, called REPNET, based on a precedence network plotted on a resource-space chart and presented with a flow-line chart. The heuristics of REPNET are used to carry out resource timing while optimizing processes flows and resource usage. The method has been tested on a sample project.

La gestione della fase esecutiva del processo edilizio, Construction Management, ha come processo fondamentale la pianificazione ed il controllo. In pratica la programmazione dei lavori è spesso realizzata tramite tecniche reticolari come il PDM, tuttavia ricercatori ed operatori ritengono che le tecniche reticolari non siano del tutto adeguate per la costruzione, in quanto non sono focalizzate sull'impiego delle risorse ed il loro flusso nel progetto. Si propone quindi un metodo di programmazione che ottimizzi la schedulazione delle risorse, il REPNET, che è una procedura euristica basata su di un reticolo PDM organizzato in un piano risorse-spazio e presentato con la tecnica flow-line. Il REPNET procede alla programmazione delle risorse ottimizzandone sia l'impiego che il flusso del lavoro, come presentato con un semplice esempio.

Keywords: construction management; project planning; activity network; resource scheduling; location based scheduling

Parole chiave: construction management; processo edilizio; metodi reticolari; programmazione risorse; programmazione location-based

INTRODUCTION

Project planning and control are core processes for Construction Project Management. In practice construction project scheduling is often accomplished with Activity Network. The most powerful networking technique now available for project planners is Precedence Diagramming Method (PDM) which can be easily implemented with a computer software. PDM is a Critical Path Method (CPM) networking technique, so it is a construction model in which a set of elements, called activities, are linked each other with logical relationships. This construction model represents building process by means of time flow between the network or the sequence of the activities that constitutes construction phases. But at the same time it represents another flow in the network, the workflow. Actually networking planning techniques are discrete and time oriented, instead construction process is a continue flow of operations (Tommelein, 1999). The success of network planning in term of use by construction planners is due to the fact that it is easily implemented by planning applications, and that its model is well suitable to the traditional conceptualization of construction (Koskela, 1992), ie workflow is not highlighted and the focus is on conversion activities.

Despite its extensive use this method have a number of shortcomings (Adeli, 1999):

- network planning do not guarantee the work continuity requirement, which may result in crew being idle;
- multiple crew strategies are difficult to implement in network planning, as resources are simply loaded on activities like features or labels;
- network diagram is not suitable for monitoring the progress of the workflow in the project;
- network methods do not provide an efficient structure for the representation of repetitive tasks, in fact all tasks are represented similarly and there is no consideration of the location of work in the scheduling process.

In fact construction projects are projects in which the physical dimensions of the building product are such to need to divide the project in smaller locations, called space units, as to better organize the work of various resources, construction crews, moving from one unit to another, i.e. performing repetitive activities in different locations. For example a concrete crew in a multi-storey building needs to move from one floor to another, or from one unit to another one to perform concrete work in the project.

It is easy to note that this is the real essence of most large and complex construction projects. Kenley and Seppanen (2010) observed that the need of organizing the construction process performed by resources in different location needs the implementation of a "Location-Based Management System".

RESEARCH METHODOLOGY AND LITERATURE REVIEW

The objective of the research is to define an heuristic procedure to help inexperienced construction project planners in the resource – constrained scheduling process.

Two main tasks are tackled in the present research: the planning and scheduling procedure must be such as to permit inclusion of work-continuity requirement; and the project duration found must be minimized in order to minimize project cost, overhead cost in particular.

Construction project are location – based projects (Kelley, Seppanen, 2010), where resources perform the same activity in different locations consecutively. So resource flow tracking is a main issue in construction planning and control. Resource – flow tracking is achieved by plotting the project PDM network on a resource space chart and showing the flow – line view of the project. As crews perform activities from a space unit of the project to another one, it might be advantageous to arrange for such crews to work continuously, without interruptions, thereby preventing idle intervals of equipment and manpower (Selinger, 1980). In fact scheduling process performed with networking techniques often prevent to satisfy the work continuity requirement because of the time relationship between activities is of the kind: "greater-than or equal-to", and the search of the minimum total project duration performed by the algorithm often prevent the finish of one activity to coincide with the start of the successor activity on the same resource path, with the introduction of an interruption of the work flow.

Because of it is believed that minimum total project duration search is of capital importance in construction projects, the work continuity constraint is relaxed in the constant resource allocation phase. Indeed a further optimization is implemented to achieve these two goals with resource loading modification.

Many scheduling methods have been proposed in literature in order to improve construction project efficiency.

El-Rayes and Mosehli (1998) suggested that resource – driven scheduling accounts directly for crew work continuity and facilitate effective resource utilization. They suggested that resource – driven scheduling of repetitive activities requires the satisfaction of three constraints: precedence relationship, crew availability and crew work continuity. Harris and Ioannou (1998) created the scheduling repetitive model that ensures continuous resource utilization with a flow view and a PDM view of the model. Arditi, Tokdemir and Suh (2001, 2002) integrated non – linear and discrete activities into LOB calculations and defined time and space interdependencies among activities as a base concept for repetitive project scheduling.

Kang et alii (2001) observed that in a multiple repetitive construction project construction cost and duration are dependent on: number of work areas, proper crew grouping, size of work areas, frequency of repetition of each activity, and provided an heuristic approach to allow optimal construction planning.

Yang and Ioannou (2001) proposed a scheduling method with focus on practical concerns in repetitive projects, in particular implemented the pulling effect in the continuity relationship between activities. Kenley and Seppänen (2009, 2010) observed that locations are important in construction because building can be seen as a discrete repetitive construction process, a series of physical locations in which work of variable type and quantity must be completed. They also observed that the location based methodology does not exclude Critical Path Method (CPM), in fact dependencies between activities in the various locations and between tasks that are made up of activities of the same work item are realized with CPM logic links.

In summary, construction site space is an important concept and viewpoint for understanding characteristics of repetitive construction projects. The earlier research has covered already several important methodological characteristics of construction planning and scheduling with the site space on focus. Although not covered explicitly here some research has covered also computerized assistance for the generation of alternative plans and schedules – for example (Kahkonen, 1994; Märki et al, 2007). The research to be presented in the following chapters is also targeting to produce such a solution that would incorporate characteristics of repetitive construction operations and to present this together with computerized assistant that would enable efficient high quality scheduling.

REPETITIVE NETWORKING TECHNIQUE (REPNET): BASIC PRINCIPLES

With the aim of improving resource scheduling in construction projects with Precedence Diagramming Method, an heuristic algorithm for construction scheduling with repetitive activities in different project locations called REPNET is developed, based on a precedence network plotted on a resource–space chart (Bragadin 2010, Bragadin, Kahkonen 2011). In construction projects it is important that repetitive activities are planned in such a way as to enable timely movement of crews from one unit to the next, avoiding crew idle time. This is known as the “work continuity constraint” and its application during project planning can provide an effective resource utilization strategy that can lead to: maximization of the benefits from the learning curve effect for each crew; minimization of idle time of each crew; minimization of the off-on movement of crews on a project once work as begun.

RESOURCE-FLOW TRACKING WITH A RESOURCE – SPACE CHART

A Precedence Diagram Network of the repetitive project is plotted on a resource – space chart, with the x-axis representing resources and the y – axis representing space units of the project. So the network node representing the activity is identified by two coordinates: the main resource performing the activity and the work space in which the activity is to be performed. The procedure of plotting the network on a resource – space coordinates has been used by many researchers in the past. In particular Yi, Lee and Choi (2002) presented an heuristic method for network construction and development for repetitive units project, with the aim of minimizing total project duration by reducing idle time of resources and spaces. Actually the heuristic changes the sequence with which crews complete the scope of work encompassed in each repetitive activity. About this procedure Moselhi and Hassanein (2004) observed that this approach and general formulation has been applied in earlier and more accurate models (e.g. El Rayes and Moselhi, 1998) and that the Yi, Lee and Choi method does not guarantee a global optimum solution.

Resources in the x-axis of the chart are generally the work crews or the equipments that perform activities. Resources are grouped by work item i.e. masonry, plastering, floor concrete slab etc. Multiple resources, i.e. crews, are allowed for the same work item in order to perform parallel repetitive activities in different locations for the same task. In this way in every column of the chart activities are grouped by resources (fig. 1).

Space units of the project are plotted on the y-axis. Space units are the locations where only one crew can perform one activity at a time. If requested, a more complex Location Breakdown Structure (LBS) can be displayed on the y-axis with a hierarchical decomposition of project locations.

An activity is defined as the set of construction operation performed by a specialized crew or equipment in a space unit of the construction project. In a repetitive construction project a set of activities, performed by the same crew in more than one space unit is defined repetitive activity. Resources that perform a repetitive activity are identified by a j code. A task is defined as a set of repetitive activities performed by one or more than one crew for a work item, and is identified by the i code. So a resource path is completely identified as a repetitive activity by the ij code (ie resource path) and a single activity is identified by the ij-k code where k identifies the space unit where the activity is performed (i.e. space path, fig. 1).

Plotting the PDM network on a Resource – Space chart makes easier resource tracking, in fact each column of the chart identify a j resource path through the project and the logical relationships between activities of the same task or repetitive activity represent resource flow tracking, while each k row of the chart identify a space units of the project and make possible to detect unit path where the relationships between activities performed by different trades represent physical or technological dependencies (fig. 1).

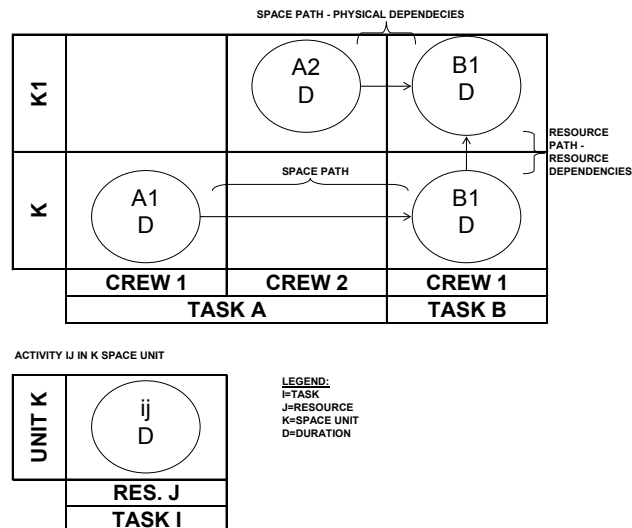


Figure 1: Network Diagram plotted on a Resource-Space Chart (adapted from Yi, Lee and Choi, 2002).

WORK CONTINUITY REQUIREMENT

After PDM critical path analysis, minimum construction project duration is found and As Soon As Possible (ASAP) project schedule is detected with Early Start (ES) and Early Finish (EF) of activities. Critical Path is detected and Free Float (FF) and Total Float (TF) for every activity can be found. In general non-zero link lags due to early time position of activities belonging to the same resource path prevent the ASAP schedule from satisfying the work continuity requirement. The proposed method aims at minimizing idle time of crews by activity shifting. Since that the REPNET optimization algorithm does not modify total project duration (TPD) as computed by traditional forward pass of Precedence Diagramming, the work flow continuity can be obtained only if made possible by network logic, activity float and feasible resource modification. If the work continuity requirement is satisfied

for every activity of a resource path, the resource path is defined critical (figure 1).

The idle time of crew j on a resource path ij between the k' predecessor space unit and the k successor space unit, is computed as the difference between the Early Start (ES) of the successor $ij-k$ activity and the Early Finish (EF) of the predecessor $ij-k'$ activity:

$$\text{Idle } ij (k',k) = \text{ES}_{ij-k} - \text{EF}_{ij-k'} \quad (\text{eq.1})$$

If there are no work interruptions between all the activities of the same resource path, the path is defined critical resource path.

Work interruption can be detected in the same way between activities of different tasks in the same space unit. If there are no work interruptions between all the activities of the various task on a space unit, the space unit is defined critical.

The idle time of work on a space unit k , between activities belonging to the ij' predecessor task and the ij successor task is computed as the difference between the Early Start of the successor activity $ij-k$ and Early Finish of the predecessor activity $ij'-k$:

$$\text{Idle } k (ij',ij) = \text{ES}_{ij-k} - \text{EF}_{ij'-k} \quad (\text{eq.2})$$

For every resource path ij the algorithm seeks for idle time of resource minimization shifting the predecessor activity ($ij-k'$) forward in time with the free float limit, if available. The activity shifting process starts from the last resource path and proceeds backward to the first one (Bragadin, 2010).

Contingency Buffer

The resource- space chart enhances Location Based Scheduling. The activities itself are defined as a set of work operations on a single space unit. The focus is on the process performed on a sequence of locations by resources. So the flow of resources must be protected with buffers to allow for variability (Kenley and Seppanen, 2009). Buffer is a time allowance provided to absorb any disturbance between two activities or tasks.

Contingency Buffers (CB) are placed at the end of every sub critical task (i.e. resource path ij) to protect Time Critical Path from overruns, and, if needed, at the end of the project to maintain the minimum project total duration.

PROJECT WORKFLOW OPTIMIZATION

While the process of scheduling tasks with the work continuity requirement usually causes an increase of the total project duration (Selinger 1980, El Rayes and Moselhi 1998, Vanhoucke 2006), the REPNET procedure prevent this effect by keeping unchanged the original CPM total project duration. Anyway this process consumes float in the schedule augmenting the number of critical activities in the schedule, so the lack of robustness of the schedule in terms of capability of delay absorbing is hindered by contingency buffers insertion.

For a further optimization of the construction process total duration the flow line view of construction project is considered.

Tasks which are proceeding faster or slower can be detected by the slope of the flow-lines. Faster tasks will have a greater slope than slower ones. So the schedule can be optimized further by changing the production rates so that the slopes of preceding and succeeding tasks are aligned to be as close to parallel as possible (Lowe, D'Onofrio, Fisk, Seppanen 2012). The alignment optimization can reduce further total project duration, but the duration gain is instead used to insert a project buffer to prevent contingency at a project level (Steyn, 2000).

The production rates for optimized tasks can be changed by adjusting resources allocation for the specific set of activities. Crews can be increased or decreased until the slope of the task is similar to its predecessor, or until no more resources are available or the lower threshold limit for activity performing is reached (Kenley, Seppanen, 2010).

Schedule performance measurement

The measurement of the schedule improvement achieved by REPNET optimization is based on Idle Time Indicator (ITI) for the resource path ij that is computed as the ratio between the sum of the idle times of the crew ij and the overall time duration of the repetitive activity DA_{ij} computed from the start

time of the activity of the crew on the first repetitive unit and the finish time of the activity on the last unit of the resource path:

$$ITI_{ij} = [\sum Idle_{ij} (k1, kn)] / DA_{ij} \quad (eq.3)$$

The Idle Time Indicator is computed for each resource path before and after the REPNET procedure to detect schedule efficiency.

REPETITIVE NETWORKING TECHNIQUE: SCHEDULING PROCESS

The heuristics of REPNET carry out resource timing in three phases: in the first phase traditional PDM as soon as possible project schedule is performed; in the second phase the REPNET algorithm search for resource scheduling optimization by minimization of resource idle time in repetitive activity performance keeping constant the resources of each crew. The work continuity requirement fulfillment is achieved by activity shifting within the free float limit. In the third phase the project workflow optimization is performed by flow-line alignment procedure through a new resource allocation procedure. The work continuity constraint is relaxed in order to maintain the PDM minimum project duration. In this way, besides the classic time critical path, a resource critical path is detected. Space critical path can be highlighted if useful. Time buffers are inserted to prevent from delays due to contingency (Bragadin, 2010).

REPNET: SAMPLE APPLICATION

The proposed method is performed for a simple example project. The example concerns a small construction project of renovation of a five storey building. Three tasks are considered: concrete slab pouring (A), plastering (B) and paving (C). These three tasks must be performed by crews in every space unit of the project. The Location Breakdown Structure (Kelley, Seppanen, 2010) is very simple, and consists of five space units which are the five floors of the building.

The example project has the following assumptions: only one crew for concrete slab pouring (A1) and for paving (C1), two crews for plastering (B1 and B2). The working hypothesis is that work assignment is a constant of the project and so labor – days for each activity on a space units are fixed. Activity duration computation is simply found by division of labor days with the number of crew laborers. Activity data for the example project are listed in table 1 below.

TASK [i]:	A - CONCRETE SLAB				B - PLASTERING				C - PAVING			
	POURING											
SPACE UNIT [k]	CREW [1]	No. Laborers [2]	Labor-days [3]	DUR. [4]	CREW [1]	No. Laborers [2]	Labor-days [3]	DUR. [4]	CREW [1]	No. Laborers [2]	Labor-days [3]	DUR. [4]
1	1	5	25	5	1	3	24	8	1	4	28	7
2	1	5	25	5	2	3	24	8	1	4	28	7
3	1	5	25	5	1	3	24	8	1	4	28	7
4	1	5	25	5	2	3	24	8	1	4	28	7
5	1	5	25	5	1	3	24	8	1	4	28	7

Table 1: Example: activity data phase 1

In every space unit k network logic is due to technological links between activities, so A – concrete slab pouring – is predecessor of B – plastering – and B is predecessor of C – paving – as shown in the activity network plotted on a resource / space chart in figure 2. Finish to Start relationships link activities performed by the same crew in different project locations, thus defining the sequence of activities performed by one crew in different space units showing the resource flow in the construction project. The activity sequence for every crew is set by project planner and in the example is starting from unit 1 and finishing in unit 5, following the units numbers. REPNET is then performed.

PHASE 1 – RESOURCE – SPACE CHART NETWORK

The PDM network is plotted on a resource – space chart (figure 2). Forward pass is performed and early activity dates are detected. Thus time critical activities are identified and time critical path of the sample project is composed by the following activities: A1-1, B1-1, C1-1, C1-2, C1-3, C1-4, C1-5. Non – zero idle time repetitive activities are found only in resource paths B1 and B2, while A1 is already a resource critical path.

The flow line chart or production lines (Selinger, 1980, Kenley and Seppanen 2010) of figure 3 shows activities represented by lines on a time / space chart, where time is plotted on the x-axis and space units are plotted on the y-axis. The activities are the lines starting from the lower left corner (start of location, start of duration) to the upper right corner (end of location, end of duration). In general, since activities are performed by a single crew, the lines represent crews passing through locations. The activities of a same resource path are linked each other by arrows representing the Finish To Start (FTS) relationships. Solid arrows are FTS links with no lag, dashed arrows are FTS links with non-zero lag, i.e. with crew work interruption. The flow line of the ASAP schedule shows work flow discontinuity between predecessor and successor space units in the afore mentioned sub-critical paths.

	Resource Path:	A1	B1	B2	C1
Phase 1	ITI #1:	0	0.14	0.11	0
Phase 2	ITI #2:	0	0.14	0	0
Phase 3	ITI #3	0	0	0	0

Table 2: resource path ITI computation

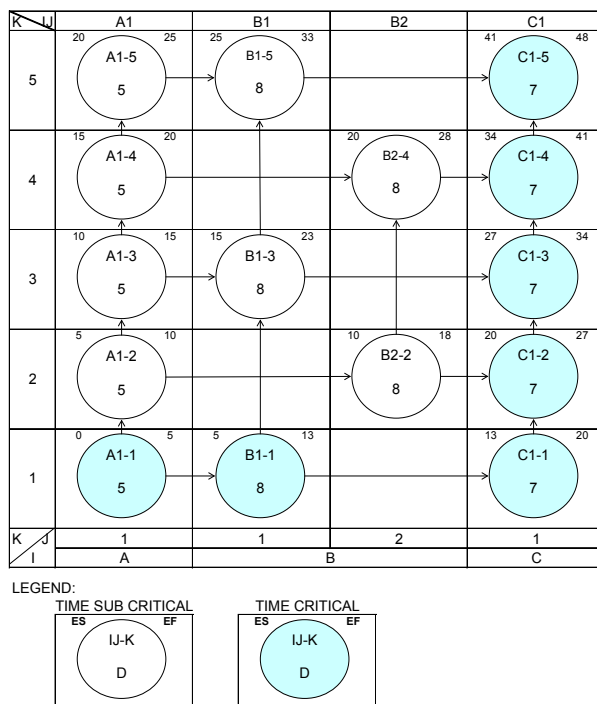


Figure 2: Example project Resource – Space Network diagram REPNET – phase 1 ASAP schedule

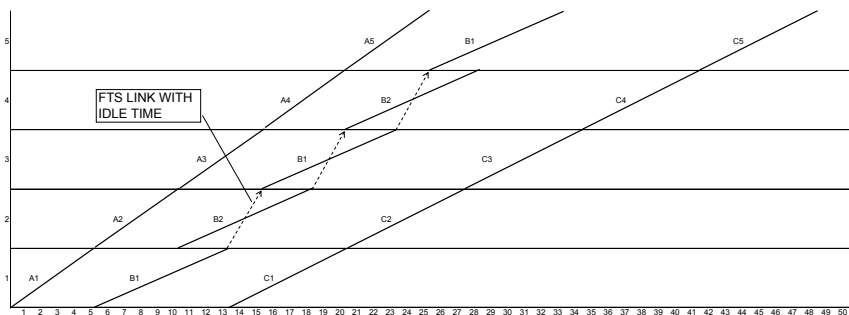


Figure 3: REPNET: Flow line of ASAP scheduling.

The Idle Time Indicator (ITI) for every resource path ij (eq. 3) is computed and showed in table 2 for phase 1.

PHASE 2 – RESOURCE PATH OPTIMIZATION WITH CONSTANT RESOURCES

After insertion of contingency buffers at the end of resource path B1 and B2, idle time of resources are diminished by activity shifting. Resource path B1 cannot be optimized due to float absence, but resource idle time in resource path B2 can be completely eliminated.

As before mentioned, resource paths A1 and C1 are already optimized (figure 4).

The flow line of the phase 2 schedule shows work flow discontinuity in the afore mentioned resource path (figure 5). The Idle Time Indicator (ITI) for every resource path ij in phase 2 is computed and showed in table 2.

PHASE 3 – PROJECT WORKFLOW OPTIMIZATION

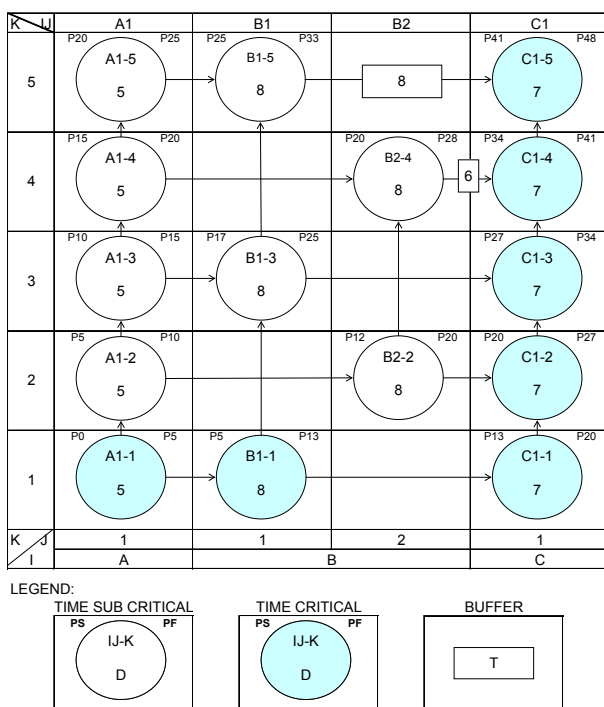


Figure 4: REPNET Example project: phase 2 optimized schedule

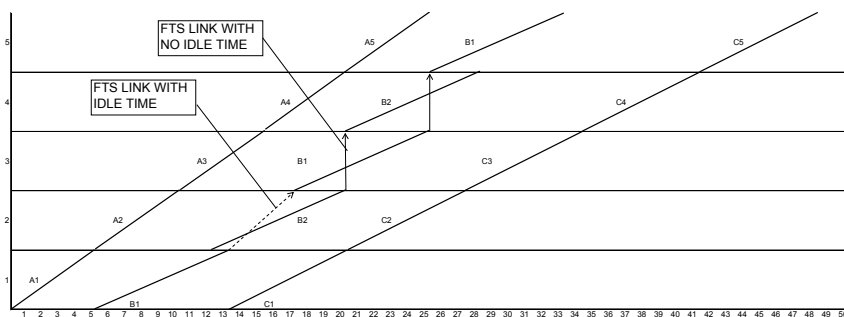


Figure 5: REPNET: flow line of phase 2 – resource path optimization with constant resources.

REPETITIVE ACTIVITY [i]	A - CONCRETE SLAB POURING				B - PLASTERING				C - PAVING				
	SPACE UNIT [k]	CREW [j]	No. Labore	Labor-day ⁴	DUR. D	CREW [j]	No. Labore	Labor-day ⁴	DUR. D	CREW [j]	No. Labore	Labor-day ⁴	DUR. D
1		1	5	25	5	1	2	24	12	1	5	28	6
2		1	5	25	5	2	3	24	8	1	5	28	6
3		1	5	25	5	1	2	24	12	1	5	28	6
4		1	5	25	5	2	3	24	8	1	5	28	6
5		1	5	25	5	1	2	24	12	1	5	28	6

Table 3: REPNET sample project: activity data phase 3

The Resource path B1 is the only one with non – zero ITI, and so needs further optimization. Personnel of crew B1 is reduced of one laborer to augment activity duration and eliminate resource idle time. While resource path B2 does not need any further optimization resource path C1 needs to be shortened to avoid total project duration augmentation. So crew C1 is incremented of one laborer, thus diminishing the task C overall duration. Results are rounded to the next integer (table 3). Due to activity duration changes contingency buffers of phase 2 are modified, and a Project Buffer is inserted after the final activity to maintain the initial ASAP total project duration. The REPNET final network is presented in figure 6 and the corresponding flow line in figure 7. Due to complete optimization of all the project resource paths, the Idle Time Indicator (ITI) is always equal to zero as showed in table 2.

CONCLUSION

The REPNET heuristic procedure for resource based construction process optimization is a semi/automatic procedure that can help inexperienced planner in repetitive construction project scheduling. The optimization process carry out resource timing in three phases: resource – space network implementation, schedule optimization with constant resources and final schedule optimization with resource allocation modification. In the first phase a traditional PDM network is plotted on a resource – space chart and the as soon as possible project schedule is performed. Flow view of construction project is showed to highlight idle times of crews. In the second phase the REPNET algorithm search for resource scheduling optimization by minimization of resource idle time in every resource path on repetitive space units, keeping constant resource allocation. The work continuity constraint is relaxed in order to maintain the PDM minimum project duration. In this way, besides the classic time critical path, resource critical paths are detected. Space critical path can be highlighted if useful. In the Third phase the REPNET algorithm proceed to process optimization by resource allocation modification, with the goal of work continuity constraint application in every resource path, while maintaining the total project duration computed in the first phase.

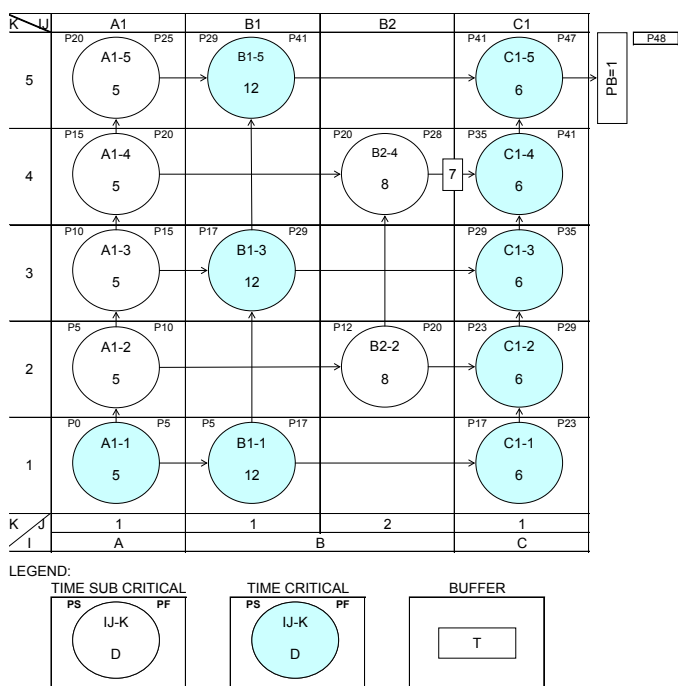


Figure 6: REPNET Example project: phase 3 optimized schedule

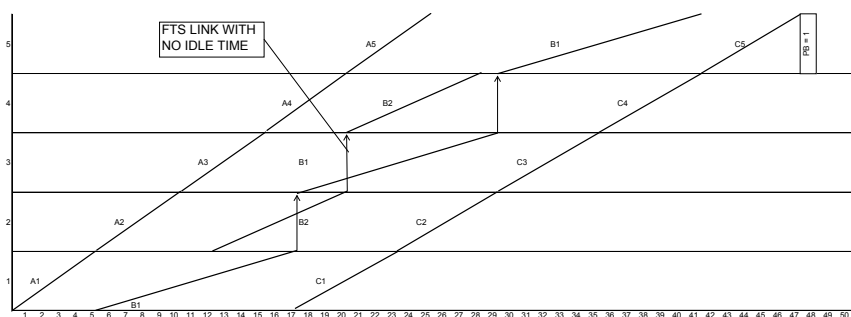


Figure 7: REPNET: flow line of phase 3 – project workflow optimized

Some of the critical elements of traditional Network Scheduling for construction projects are tackled by implementing workflow optimization through Location Based-Scheduling and flow-line graphs. In particular the resource driven scheduling is implemented by network definition on the resource – space chart, where for each activity resources and location are set in one time. These features of the scheduling model make possible to implement resource - flow tracking, i.e. the view of the planner of the movement of resources through the construction project. Also the flow-line view shows the workflow, the production rate and the use of resources (e.g. crews and equipment) on the same graph, thus providing an easy-to-control schedule, improving the control phase during project execution.

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IV

Schedule Health Assessment for Construction Projects

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Schedule Health Assessment for Construction Projects

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ABSTRACT

Purpose of this paper

The aim of the research is to assess the quality of the schedule of a construction project, and the characteristics that a good quality schedule should have. This can be defined as "Schedule health Assessment".

Design/methodology/approach

Very few research has been found to be inherent to quality of schedules, and most of it is not construction oriented. Although a set of quality requirements applicable to a construction schedule have been defined by literature review and by experience from practical implementation. The set of quality requirements defines a metric to measure schedule quality. The schedule requirements have been classified and weighted related to their importance and a method of schedule health assessment has been developed. The method can help project planners to produce a good quality schedule since the initiating of the project and, during the execution phase, it can be used to perform a schedule health assessment to detect deficiencies and issues to be addressed for construction control purposes.

Findings and value

Quality assessment of a construction project schedule is a challenging task. The paper defines a metric to measure schedule health assessment for construction projects.

Research limitations/implications

A future commitment is needed to develop a semi-automated tool to perform health assessment of schedules.

Practical implications

Outcomes and implication for practical implementation in a construction project team are broad. In fact construction schedule is one of the most important element needed for complex construction project management. Good quality schedule can be considered a basic element for a good quality construction process.

Originality/value of paper

Few researchers have aimed at defining quality of project schedules, especially in the construction sector, due to project and process complexity. The value of the paper is in the development of a simple and practical method to produce and maintain a quality schedule for a construction project, though involving a complete schedule metrics.

Keywords: construction, scheduling, quality, project management, activity network

1 INTRODUCTION

Construction project management main task is to design and to control the production process of a building or a civil engineering facility, so main tool of construction management team is the project schedule. A sound project schedule merge cost and technical data to influence project management decision and actions (PMSC, 2012). Realistic schedules help construction managers and stakeholders

to make decisions, to monitor past performance and to forecast future project performance and costs. But how a realistic schedule can be defined, or in other words which are the quality characteristics of a sound and realistic construction schedule? To answer to this research question many planning standards and schedule quality assessment methods proposed by researchers and practitioners have been studied.

Quality can be defined as the level of accomplishment of a product or a process to a set of performance requirements (ISO 9000:2005). In construction projects the measure of quality performance is a complex task and, in general, construction projects are complex projects. Project success i.e. the achievement of project objectives is the main goal of project quality assessment. Griffith (2005) and the guide of the United States Government Accountability Office (GAO) report that there is a significant relationship between good scheduling practices used early in the project life cycle and the ultimate success of the project (GAO, 2009). So quality of the scheduling process and quality of the schedule itself can play an important role in the achievement of project success and represent a key process of construction project management. Quality of a construction schedule can be defined as the satisfaction of a set of requirements to specified performance indicators. The paper has the aim of contributing at the understanding of quality of construction schedules through the evaluation and definition of a set of related quality requirements. The definition of a set of quality items of construction schedules can help project schedulers to produce a good quality schedule and to perform an effective maintenance process of the construction schedule. The Schedule Health Assessment process quantifies schedule performance, thus enabling project team to implement a pro-active approach to construction scheduling.

2 LITERATURE REVIEW

Few standards and researchers have addressed the quality of the scheduling process. The AACE International (AACE) Recommended Practice No. 14R-90 (2006) describes the roles and responsibilities of a Planning and Scheduling Professional during the various phases of project planning and schedule development, management and control, also establishing a planning and scheduling guidelines for training and professional development. Scheduling is defined as the “process of converting a general outline plan for a project into a time-based schedule based on available resources and time constraints”. The recommended practice lists the elements of the scope of knowledge of the planning and scheduling process, and in this list includes the “Schedule Quality Analysis”, meaning the checking of the schedule specification compliance, the verification of the schedule integrity (i.e. schedule mechanics and constructability) and the schedule validation. The AACE Recommended Practice no. 48R-06 (2009) defines a guideline for schedule constructability review process of a construction schedule. The goal of a Schedule Constructability Review (SCR) is to assess whether the schedule is comprehensive and complete. Constructability can be defined as the use of construction knowledge and experience in planning, design, procurement and field operation to achieve overall project objectives (Douglas, Gransberg, 2009).

The Project Management Institute (2007) has described the methods related to scheduling that are generally recognized as good practice for most projects, most of the time. The Practice Standard for Scheduling of the Project Management Institute (2007) describes the schedule development process and the schedule model good practices and components. The Standard also defines a Conformance Index and a Conformance Index Assessment process to evaluate schedule quality.

The GAO “Cost Estimating and Assessment Guide” (2009), describes recommended best practices for developing and managing capital program costs of projects using public funds. The guide focuses on project cost estimating, planning and managing. It includes a broad description of the Earned Value Management System. The GAO guide includes between major reasons of project success the quality of its schedule. Schedule provide a time sequence for the duration of project activities, and should integrate the logical relationship between activities, activity resources requirements and durations, and any constraint that affect their start and completion. The GAO guide indicates 9 requirements useful to develop and maintain and integrated network schedule.

The US Defense Contract Management Agency (DCMA) has defined a 14 points metrics aimed at identifying potential problem areas with a contractor's Integrated Master Schedule (2012). The DCMA 14 point schedule metrics is a tool that supports the schedule analysis to determine whether it is a realistic schedule or not, ie gives a metrics for assessing schedule quality. The schedule quality assessment can also be performed by an automated MS Project Macro developed by the agency.

The National Defense Industrial Association (NDIA), working group of Industrial Committee for Program Management published the “Planning and Scheduling Excellence Guide (PASEG)” to provide the project management team, including new and experienced master planners/schedulers, with practical approaches for building, using and maintaining the project master schedules. The guide

encompasses “Generally Accepted Scheduling Principles (GASP), 10 quality control steps to validate the Integrated Master Schedule and a list of metrics that can be used to assess schedule health. Automated schedule health assessment is recommended.

In addition to these standards and recommended practices, several researchers searched for a deeper understanding of quality and reasonableness of construction schedule.

De La Garza et alii (1990) defined a subset of scheduling principles to enable construction schedule evaluation process for subsequent automation. An automated system called CRITEX, written for the U.S. Corps of Engineers has the purpose of critiquing construction schedules from four perspectives: general requirements, logic, cost and time of the project and of the activities. The system encompasses 34 provisions for schedule quality assessment.

Russell and Udaipurwala (2000) perspective on schedule quality assessment is related to construction strategy, “the plan of attack”, plus the timing of activities. Russell identifies various indicators of schedule quality, grouped under several headings: accuracy and completeness, consistency with other planning documents, good practice/workability and benchmarks for control. Abstraction and compliance with contract documents are quoted but not examined in the paper.

Zwikael and Golberson (2004) introduced a model for evaluating the quality of project planning called “Project Management Planning Quality (PMPQ)”. The PMPQ model estimate a schedule quality index based on 33 provisions.

Griffith (2005) demonstrated a clear correlation between schedule development and construction project success. Projects which start the execution phase with quality schedules outperforms other projects in terms of cost and time performance.

Hietala (2009) indicates a framework to develop schedules with better quality and also to assess the quality of developed schedule. General requirements for schedule quality at an upper hierarchical level of planning are: realistic, feasible, simple, make commitment, accurate and timely. Detailed planning quality assessment is performed in two steps. First it is used “Planalyzer” (Fishman I., Levitt R., 2007) a commercial system by Ibico Inc., to assess detailed schedule quality at a network level. Then it is used the detailed criteria for detailed planning quality assesment. Detailed criteria are: decomposed from Work Breakdown Structure (WBS), explicit description, logical sequence, indicate predecessor relations, well evaluated estimates, sufficiently detailed for measurement and control, standardized, highlight critical tasks, flexible modifiable and updateable, communicative, resourced, buffered.

Moosavi (2012) and Moosavi and Moselhi (2012) defined a structured methodology to assist owners in the evaluation and approval of detailed schedule of contractors. In essence it is a check list that covers a set of overall requirements for good schedules. The methodology has been implemented in an automated computer application called “Schedule Assessment and Evaluation – SAE” developed to assist owners in the review of project schedules. The SAE performs schedule evaluation in three tiers:

1. Assessment of the schedule against industry recommended practices;
2. Job logic assessment of construction trades;
3. Assessment productivity and crew size considered for a number of commonly used trades in building construction.

The method is based on the evaluation of forty eight criteria for schedule health assessment including conceptual provision as well as quantitative requirements. The criteria where divided into three major categories: contractual compliance, schedule development, and schedule components. In the first step of the research (Moosavi 2012) the criteria were first classified in conceptual provisions and quantitative provisions, than they were classified in obligatory and complementary provisions.

3 SCHEDULE HEALTH ASSESSMENT INDICATORS

3.1 Health Assessment Indicators and schedule quality requirements

Basically schedule quality is the result of the interaction between two elements, construction knowledge transferred into project schedule and schedule mechanics knowledge. By construction knowledge it is meant the set of information related to construction technology implementation in the building construction process, while by schedule mechanics knowledge it is meant the set of information related to scheduling technology, ie scheduling and activity network rules. Actually construction knowledge implementation refers to the constructability concept, as previously addressed, i.e. a system for achieving optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations in the building process, and balancing the various project and environmental constraints to achieve overall objectives (IPENZ, 2008). Actually constructability or buildability it is a project management technique to review construction processes from start to finish during pre-construction phase. It is to identify obstacles before a project is actually built to reduce or prevent errors, delays, and cost overruns. Instead schedule mechanics knowledge refers to the project management methods and techniques to plan and schedule project. As most of

construction project are scheduled with a networking technique, e.g. Precedence Diagramming Method, implemented with a computer software, schedule mechanics is the set of rules that allows the performance of the scheduling process with a critical path method on a computerized application.

While in most standards, recommended practices and pertinent literature these two different bodies of knowledge are addressed in the construction schedules with separate approaches, it is felt that an integrated approach could be more effective. So Schedule Health Assessment Indicators were developed to address both these two bodies of knowledge used for construction scheduling.

First of all, schedule quality requirements available from literature, as defined by researchers, by international standards and recommended practices, have been identified. More than one hundred specific schedule quality requirements have been evaluated and classified. Then a selected group of seventy five requirements has been individuated and classified in five groups of requirements. This five groups of requirements were defined as Schedule Health Indicators. Each schedule indicator aims at defining a quality level of schedule performance in a specific topic to assess schedule health.

The five schedule health indicators are the following:

1. General requirements;
2. Construction process requirements
3. Schedule mechanics requirements;
4. Cost and resources requirements;
5. Control process requirements.

Each indicator is, in turn, composed by a number of requirements aimed at developing a construction project schedule of a good quality level.

3.2 Detailed schedule quality requirements

The set of requirements composing each Schedule Health Indicator are defined by a subset of detailed requirements that specify the performance level to be performed by the construction schedule. In some cases the detailed requirements can be composed by another tier of more specific indicators to enhance the measurement process. The research focused 75 detailed requirements and 54 specific indicators to assess schedule quality. A complete list of detailed requirements and related specific indicators can be found in appendix n.1, where it has been included the checklist for the sample project. The following description of each Schedule Health Indicator encompasses the related set of requirements.

Indicator no.1 "General requirements" consists of a set of provisions that are aimed at conforming the schedule production process to quality standards related to the developing phase, to the schedule as a product, and to the contract requirements of the construction project (table 1). Indicator no. 2 "Construction process requirements" consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the execution phase of the construction project, i.e. to implement schedule constructability (table 2). Indicator no. 3 "Schedule mechanics requirements" consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the planning/monitoring phase of the construction project (table 3). Indicator no. 4 "Cost and resources requirements" consists of a set of provisions that are aimed at verifying that the activities of the project, and the project itself, can be executed within the calculated time and budget (table 4). Indicator no. 5 "Control process requirements" consists of a set of provisions that are aimed at allowing an efficient project control process through the schedule updating and re-planning processes (table 5). Each Schedule Health Assessment Indicator is composed of the requirements of the following list.

1. General requirements:
 - a. Schedule process procedure;
 - b. Schedule definition;
 - c. Activity definition.
2. Construction process requirements:
 - a. Activity sequencing;
 - b. Activity duration;
 - c. Activity timing;
 - d. Construction process productivity.
3. Schedule mechanics requirements:
 - a. Network and logic;
 - b. Critical path;
 - c. Float;
 - d. Soft & hard Constraints, buffers;
 - e. Activity mis-assignments;

- f. Lag & lead (negative lag).
- 4. Cost and resources requirements:
 - a. Monetary value/cost of activities;
 - b. Project cost ratio;
 - c. Resource loaded activities;
 - d. Project total level of effort.
- 5. Control process requirements:
 - a. Activity progress evaluation;
 - b. Schedule review and baseline;
 - c. Schedule projections;
 - d. Invalid dates and missed tasks.

The General Requirements indicator (tab. 1) is composed by three basic requirements: Schedule Process Procedure; Schedule Definition; and Activity definition. The Schedule Process Procedure requirement aims at conforming the schedule development process to four related quality standards as the definition of an activity coding structure, the identification of project calendars, the involvement of main subcontractors and the following of a standardized scheduling procedure. The Schedule Definition requirement entails five more detailed requirements about schedule structure and contract compliance. In particular it concerns schedule logic vertical and horizontal integration, meaning that detailed tasks must flow-up to summary tasks and there must be logical relationships and time-phasing between tasks. The Activity Definition requirement encompasses detailed requirements mainly about the total number of activities, activity name and definition, WBS, and responsibility assignment (table 1).

Table 1 General Requirements.

Schedule Health Indicator	Requirements	Detailed requirements
General Requirements	Schedule process procedure	<i>Project calendars identification</i> <i>Activity coding structure</i> <i>Main subcontractors participation</i> <i>Standardized sched. procedure</i>
	Schedule definition	<i>Milestones</i> <i>Project duration</i> <i>Master schedule & Critical path id.</i> <i>Schedule logic integration</i> <i>Realistic network logic</i>
	Activity definition	<i>Activity easy to monitor</i> <i>Total number of activity manag.</i> <i>Activity duration reasonable</i> <i>Activity name understandable</i> <i>Total scope as defined by WBS</i> <i>Submission date</i> <i>Responsibility assignment</i> <i>Special activities included</i>

Four are the basic requirements composing the Construction Process Requirements indicator: Activity Sequencing; Activity Duration, Activity Timing and Construction Process Productivity. They are mainly concerned with schedule constructability. Activity Sequencing aims at defining a construction-oriented network logic, while Activity Duration is related to the duration estimate and the continuity of production during activity execution. Activity Timing detailed requirements are mainly related to proper scheduling of weather sensitive activities. Construction Process Productivity is related to work efficiency of the construction site, and entails detailed requirements about work continuity and work flow of resources (table 2).

Table 2 Construction Process Requirements.

Schedule Health Indicator	Requirements	Detailed requirements
Construction process Requirements		
	Activity sequencing	<i>Reasonable activity sequencing Network logic used for all activities Predecessor relation indicated</i>
	Activity duration	<i>Duration definition Duration estimation Continuity of production</i>
	Activity timing	<i>Weather sensitive activities Building enclosure dependencies</i>
	Construction process productivity	<i>Work continuity Work-flow Non-congested work areas</i>

Schedule mechanics requirements indicator aims at conforming the network schedule structure to critical path method related detailed requirements. So the indicator is composed by detailed requirements related to network and logic, critical path and critical activities, float dimensions and computation, soft and hard constraints, buffers, leads and lags, activity mis-assignments (table 3).
Schedule mechanics

Table 3 Schedule Mechanics Requirements.

Schedule Health Indicator	Requirements	Detailed requirements
Schedule mechanics Requirements		
	Network and logic	<i>Open ended activities Summary tasks logic Missing logic Relationship ratio Relationship types High duration</i>
	Critical path	<i>Critical path & critical activities Critical activities features Multiple critical paths Critical path test Critical path length index (CPLI) Critical path logic Schedule criticality rate Near criticality rate Critical activity duration</i>
	Float	<i>Float computation Reasonable float dimensions Excessive total float Negative float</i>

Soft & Hard Constraints, buffers	<i>ASAP & ALAP computation Constraints Number of constraints Buffers</i>
Activity mis-assignments	<i>No activity mis-assignments No empty milestones</i>
Lag & Lead (negative lag)	<i>Number of lags No leads</i>

Table 4 Cost and Resources Requirements.

Schedule Health Indicator	Requirements	Detailed requirements
Cost and Resources Requirements		
	Monetary value/cost of activities	<i>Monetary value of activities Total monetary value Progress payment</i>
	Project cost ratio	<i>Project cost ratio range</i>
	Resource loaded activities	<i>Resource loading Resource productivity Resource conflicts</i>
	Project total level of effort	<i>Total amount working hours/days Project effort ratio</i>

Table 5 Control Process Requirements.

Schedule Health Indicator	Requirements	Detailed requirements
Control process Requirements		
	Activity progress evaluation	<i>Percentage complete Schedule slippage</i>
	Schedule review and baseline	<i>Schedule maintenance Actual progress Variance report Baseline Execution Index</i>
	Schedule projections	<i>Schedule projections Corrective actions</i>
	Invalid dates and missed tasks	<i>Invalid dates Missed tasks Out of sequence</i>

4 DEVELOPED METHOD OF SCHEDULE HEALTH ASSESSMENT

The five schedule health indicators do not have the same importance in the planning and scheduling process. While some of the studies and recommended practices focus on the requirements related to constructability (De la Garza, 1990; Dzung, Lee 1999; Douglas, 2009), which mainly corresponds to the Schedule Health indicator no. 2 (Construction process requirements), most of guidelines and standards, (PMI, 2007; U.S. DICMA, 2012; PMSC – NDIA, 2012) highlight the importance of the scheduling process and of the scheduling product quality, addressing in particular scheduling process and schedule mechanics, which are related to the Schedule Health indicators no. 1 and no. 3, (General requirements and Schedule mechanics requirements). Also Moosavi and Mosehli (2012) who performed a survey based on feedback from professionals of the construction industry, indicate as top schedule assessment criteria the ones related to the scheduling process and to schedule mechanics. Although the cost and resource loading requirements are fundamental players in the planning and controlling processes, as also are the control requirements, it seems that other indicators are more noteworthy for effective scheduling. So, as the number of detailed requirements from pertinent literature of each Schedule Health Assessment Indicator seems to be in direct relationship to the level of importance of each indicator, the developed method weights each Schedule Health Assessment Indicator in function of the number of the composing detailed requirements.

4.1 Health Assessment Procedure

The method identifies a number of measurable detailed requirements for each schedule health indicator of the construction project schedule. The detailed requirements are derived from pertinent literature and authors' experience. Detailed requirements are also selected with the aim of allowing practical and objective measurement of performance. If needed the measurement of schedule performance of a detailed requirement is achieved through more specific measurable requirements. Then the quality of each component of the construction project schedule quality is estimated on schedule indicators basis.

A weighted approach is used to aggregate the estimated quality for the considered schedule indicators to provide an overall quality of the schedule at the global level, and a comprehensive Schedule Health Assessment can be found. The Schedule Health can be quantified with a percentage grade. For each Schedule Health Indicator the weight (W_{gi}) indicates the relative importance of each indicator to the others being used to measure the overall health status of the schedule of the construction project.

$$SH = \sum_i^5 Si \times W_{gi} \quad (1)$$

where SH = overall schedule health assessment of the construction project; Si = Schedule Health Assessment Indicator (i); W_{gi} = weight of schedule health indicator (i), compared to other indicators of the schedule.

The model of equation (1) allows to measure and quantify the overall health of the construction project schedule with a practical and empirical approach.

The Schedule Health Assessment Indicator (Si) for the requirement group (i) of the scheduling process is evaluated with the percentage of adherence to detailed and specific requirements for schedule quality. The indicator is calculated with the following equation (2):

$$Si = \frac{\sum_j^s DR_{ij}}{\sum_j^s Rij} \quad (2)$$

Where Si = Schedule Health Assessment Indicator (i); DR_{ij} = estimated detailed requirements met by schedule (j) for the schedule health assessment indicator (i); Rij = total sum of detailed requirements (j) for the schedule health assessment indicator (i). Note that for each detailed requirement satisfaction the DR_{ij} value is 1, if the schedule does not meet the requirement the DR_{ij} value is zero.

5 SCHEDULE HEALTH ASSESSMENT IMPLEMENTATION AND SAMPLE APPLICATION

The developed method of schedule health assessment aims at supporting project schedulers in the project planning phase to develop master and detailed schedules, and in the execution phase, to support the controlling process.

In the planning phase the project team needs to develop a sound and detailed schedule. The planning process can be supported by the Schedule Health requirements, used in this phase as guidelines of the project management schedule sub-process. A simple application of the developed method at the end of scheduling process can quickly detect any weakness in the schedule thus allowing the project scheduler and/or the entire project team to provide a remedy or to correct the schedule. In the controlling phase the schedule health assessment method can provide correct information for schedule maintenance.

The Schedule Health Assessment is also a tool useful for owner consultants entitled to project supervision, supporting them in the objective evaluation of contractors' detailed schedule, before the commencement of the construction works or during the execution phase.

The Schedule Health Assessment developed method has the goal of being simple and easy to perform by practitioners and researchers. So the evaluation process can be performed easily by the project scheduler assessing schedule performance related to the requirement specified in the checklist. Note that the requirements list can be emended to fit to specific project needs.

The schedule health assessment can be accomplished in a straight forward manner. First the detailed requirement list is evaluated. Each Schedule Health Indicator (i.e. General requirement) is composed by requirements (i.e. Schedule process procedure, schedule definition, activity definition). Each requirement is made up of various detailed requirements, as previously defined (ref. appendix n. 1). The scheduler checks if each detailed requirement is satisfied by project schedule. For each detailed requirement satisfied by schedule model a point is earned. Then with equation (2) the value of each Schedule Indicator is found. The weighted sum of each indicator is the Schedule Health Assessment ranking (eq. 1).

A sample application has been performed on a simple detailed schedule of a construction project of a small sport facility located in northern Italy. The scheduling software used is the MS Project®. The network is composed of 179 activities (fig. 1, fig. 2).

The Schedule Health Assessment procedure was developed with the check list of appendix n.1. The final grade SH achieved by the schedule was 77% (table 6). The result obtained by the schedule was good enough for project control purposes, but suffered from a set of deficiencies. The "General Requirements" indicator earned 13 positive points out of 17, thus showing a very good schedule and activity definition process though revealing the absence of a standardized schedule process procedure. Also the "Construction Process Requirements" indicator obtained a good score of 10 points out of 11. In fact all the detailed requirements about activity sequencing, activity duration, activity timing and construction process productivity were properly implemented. Also the schedule health indicator no. 3, "Schedule Mechanics Requirements" had a very good grade, 26 points out of 27. In fact all schedule requirements about computerized networking technique implementation were satisfied by the sample schedule. Network logic was clear and correctly implemented, critical path and float definition were properly defined, no activity mis-assignments and no negative lags were found. Soft and hard constraints requirement was substantially satisfied. Instead no monetary value and no resources have been loaded, so no points were earned by the schedule for the "Cost and Resources Requirements" indicator. The last indicator considered was the "Control Process Requirements" indicator which earned 9 points out of 11. Most of the requirements were considered fulfilled, and to be more specific activity progress evaluation and schedule projections were considered well implemented, while schedule review and baseline definition suffered some deficiencies. No invalid dates and missed tasks were found.

Figure 1 Fragnet sample schedule.

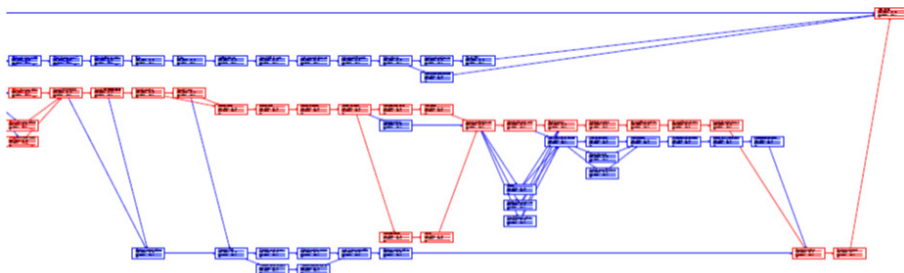


Figure 2 Snapshot from analyzed sample schedule.

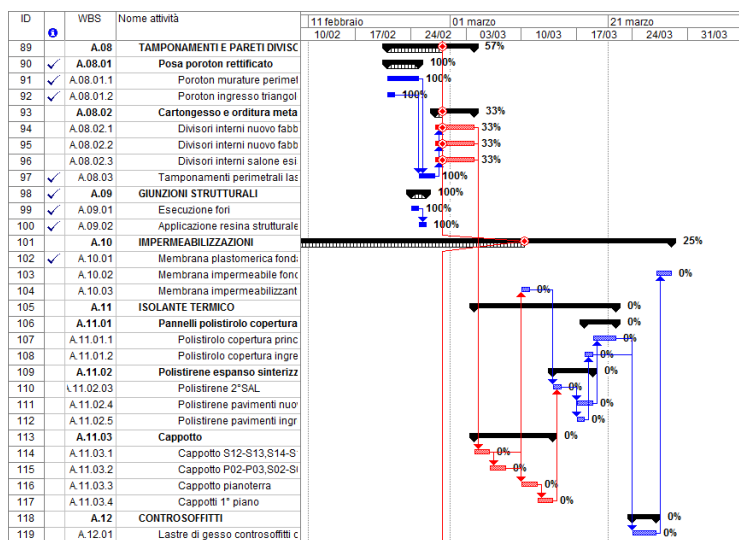


Table 6 Sample schedule health assessment.

No. Req.	Requirement description	Req. score	indicator score	Wg	Si	Swi
1)	General requirements (17):		13	23%	76%	18%
a.	Schedule process procedure (4);	1				
b.	Schedule definition (5);	5				
c.	Activity definition (8);	7				
2)	Construction process requirements (11):		10	15%	91%	14%
a.	Activity sequencing (3);	3				
b.	Activity duration (3);	3				
c.	Activity timing (2);	2				
d.	Construction process productivity (3)	2				
3)	Schedule mechanics requirements (27):		26	36%	96%	35%
a.	Network and logic (6);	6				
b.	Critical path (9);	9				
c.	Float (4);	4				
d.	Soft & hard Constraints, buffers (4);	3				
e.	Activity mis-assignments (2);	2				
f.	Lag & lead (negative lag) (2);	2				
4)	Cost and resources requirements (9):		0	12%	0%	0%
a.	Monetary value/cost of activities (3);	0				
b.	Project cost ratio (1);	0				
c.	Resource loaded activities (3);	0				
d.	Project total level of effort (2)	0				
5)	Control process requirements (11):		9	14%	82%	11%
a.	Activity progress evaluation (2);	2				
b.	Schedule review and baseline (4);	2				
c.	Schedule projections (2);	2				
d.	Invalid dates and missed tasks (3).	3				
SH =						77%

6 CONCLUSION

A Schedule Health Assessment method has been developed. The method has the aim of being a proactive quality control tool for the detailed construction scheduling.

The method identifies five Schedule Health Indicators which can be quantified by the evaluation of schedule quality requirements satisfaction by project planners. As some requirements are more important than others, a weight system of requirements groups has been developed. The weighted sum of the performance level of each indicator for the construction schedule under evaluation is defined as the Schedule Health Assessment.

Seventy five requirements were selected from literature and standards, thus enabling an in-deep evaluation of a construction schedule. This requirement list should be used by project planners and schedulers from the start of the scheduling process. In this phase the conformance of the schedule with scheduling requirements helps the scheduler to produce a good level schedule. At the end of the scheduling process the conformance of the project schedule with the requirement list gives the project team the metric to detect the schedule quality level or, in better words, to perform the Schedule Health Assessment. The developed method can also be used by owner's consultant to evaluate contractor's detailed schedule.

During the execution phase of the construction project the requirement list helps project team and schedulers to perform schedule maintenance thus allowing an efficient monitoring and controlling process.

The developed method was tested on a sample construction project schedule. The method was able to highlight critical elements and strength features of the construction schedule, performing a simple but accurate analysis.

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APPENDIX 1

Figure 2. Sample Project Checklist part #1.

SCHEDULE HEALTH ASSESSMENT /1					
PROJECT:		PROGETTO ORATORIO IT			
START DATE		12/11/2013			
STATUS DATE		28/02/2014			
Schedule Health indicator	Requirements	#	Detailed requirements specific requirements	score	total score notes
1. General requirements:					13
a. Schedule process procedure;					1
		1	Project calendars are identified	1	0 or 1
		2	Activity coding structure	0	0 or 1
		3	Main subcontractors participation is requested	0	0 or 1
		4	The schedule process is adherent to standardized scheduling procedure	0	0 or 1
b. Schedule definition;					5
		5	Milestones (at least two: project start and project finish)	1	0 or 1
		6	Project duration (compliance with the overall contract start and completion dates)	1	0 or 1
		7	Master schedule and critical path must be identified.	1	0 or 1
		8	Schedule logic should be vertically and horizontally integrated	1	0 or 1
		9	Vertical schedule integration violation: all tasks should flow up to their summary task		
			Schedule reflects realistic and meaningful network logic / phasing and sequencing	1	0 or 1
c. Activity definition;					7
		10	Activities can be easily monitored and measured (ie they are real)	1	0 or 1
		11	Total number of activities should remain manageable Number of activities: The number of activities it has to be within a min/max range (if not set by contract provisions)	1	0 or 1
		12	Activity duration must be reasonable	1	0 or 1
		13	Activity name is understandable/usable	1	0 or 1
		14	All the activities provide the total scoping of the project/each element of the project scope as defined in the WBS, is supported by one or more activities;	1	0 or 1
		15	Activity/schedule submission date	1	0 or 1
		16	Responsibility. Responsibility assignment	0	0 or 1
		17	Special activities should be included:	1	0 or 1
			- Start up and testing activities		
			- Procurement activities		
			- Permits and environmental remediation		
			- Submittal activities		
			- Submittal review activities		
2. Construction process requirements:					10
a. Activity sequencing;					3
			Reasonable activity sequencing. Activities' interdependencies and sequencing should be logical / reasonable.	1	0 or 1
			- Activities may be overlapped without affecting production continuity.		0 or 1
			- Tasks with explicit names in logical sequence with right dependencies		0 or 1
			- Complete specification of logic in order to maintain construction strategy (under all date scenario: early, levelled, late);		0 or 1
			Network logic used for all activities. All activities must be sequenced and related using network logic.	1	0 or 1
		19		1	0 or 1
		20	Predecessor relation should be indicated	1	0 or 1
b. Activity duration;					3
		21	Duration definition. Activity duration should be defined taking into account the following features.	1	0 or 1
			- Duration limits range from 1 to 30 days (detailed activity) / planning packages requiring detail planning		
			- Critical activities should be more detailed (1 to 20 days)		
		22	Duration estimation based on evaluation and previous experience	1	
			- Specification of duration as function of construction methods, resource levels, site conditions, design features, regulatory environment / estimated realistically		
		23	Continuity of production in the activity should be maintained.	1	
c. Activity timing;					2
			Weather sensitive activities. The duration should reflect the season of the year in which activities are to be executed (if weather sensitive, ie its materials and/or labor are affected by either water, temperature or moisture);	1	0 or 1
		24	Building enclosure dependencies. The building enclosure should be logically related to weather-sensitive activities. A building is considered enclosed when weather sensitive-work can proceed and the building can be heated.		
		25		1	0 or 1
d. Construction process productivity					2
			Productivity maximization through:		
		26	Work continuity;	0	0 or 1
		27	Workflow / Orderly flow of work;	1	0 or 1
		28	Non-congested work areas;	1	0 or 1

Figure 3. Sample Project Checklist part #2.

SCHEDULE HEALTH ASSESSMENT / 2					
PROJECT:		PROGETTO ORATORIO IT			
START DATE		12/11/2013			
STATUS DATE		28/02/2014			
Schedule Health Indicator	Requirements	#	Detailed requirements specific requirements	total score	notes
3. Schedule mechanics requirements:				26	
a. Network and logic				6	
		29	Open ended activities (activities without affiliation) should be avoided	1	0 or 1
		30	Summary tasks with logic relationships should be avoided	1	0 or 1
		31	Missing logic: there should not be any incomplete tasks with missing logic	1	0 or 1
		32	Relationships ratio: total number of relationships/total number of activities should be limited	1	0 or 1
		33	Relationship types (FS, SS, FF, SF). Start to Finish SF is counter-intuitive, it should be avoided	1	0 or 1
		34	High duration: the number of incomplete tasks with high duration should be limited	1	0 or 1
b. Critical path				9	
		35	Critical path & critical activities identification <i>An activity is considered critical if its first likely delay causes a delay in the overall completion date.</i>	1	0 or 1
		36	Critical activities features. The logic, cost, duration and number of activities on the critical path should be reasonable	1	0 or 1
		37	Multiple critical paths. Managing simultaneous critical path is difficult and should be avoided whenever possible	1	0 or 1
		38	Critical path test. Critical path should be continuous through the network, ie there must not be broken logic which is the result of missing predecessor and / or successor on task where they are needed. The schedule passes the test if the project finish date matches the added delay into the remaining duration.	1	0 or 1
		39	Critical path length index (CPLI). Project schedule's Critical Path Length (CPL) is the length in work days from time now until the next project milestones that is being measured. Total Float (TF) is the amount of days a project can be delayed before delaying the project completion date. - Critical Path Length Index (CPLI) = (CPL + TF) / CPL - The CPLI value should be greater than 1.00. - Critical/driving path analysis. Perform critical and driving path analysis to the program end and interim milestones. Analyze and mitigate impacts by using schedule acceleration techniques.	1	0 or 1
		40	Critical path logic. Each critical activity should have a predecessor reflecting a physical dependencies	1	0 or 1
		41	Schedule criticality rate. Schedule criticality rate #1: number of critical activities/total number of activities should be limited - Schedule criticality rate #2: duration of critical activities/total duration of activities should be limited	1	0 or 1
		42	Near criticality rate: number of near critical activities / total number of activities should be limited (near critical activities: TF<5 to 10)	1	
		43	Critical activity duration: the duration of critical activities should be limited to be well manageable	1	0 or 1
c. Float				4	
		44	Float computation. The amount of time a task can slip before affecting the critical path for activities must be calculated	1	0 or 1
		45	Reasonable float dimensions. Float should be broad enough to support the premise that it as not been manipulated	1	0 or 1
		46	Excessive total float. Activity with excessive total float should be avoided. - High float: an incomplete task should not have total float greater than 44 days (2 months). The percentage of task with total float greater than 44 days should not exceed 5%. - High Float % = (total # of incomplete tasks with high float)/(total # of incomplete tasks) x 100	1	0 or 1
		47	Negative float. No activities with negative float are allowed. Negative float: an incomplete task should not have total float less than 0 working days. There should not be any negative float in the schedule. Negative Float % = (total # of incomplete tasks with negative float)/(total # of incomplete tasks) x 100	1	0 or 1
d. Soft & hard Constraints, buffers				3	
		48	ASAP & ALAP computation. The schedule model calculates early start and late start and finish dates for each activity	1	0 or 1
		49	Constraints must not be used in the schedule model to replace schedule logic	1	0 or 1
		50	Number of constraints. The number of constraints on activities start and finish should be limited - Soft constraints: ASAP, start no earlier than (SNET), finish no earlier than (FNET) - Hard constraints: must-finish-on (MFO), must-start-on (MSO), start-no-later-than (SNLT), finish-no-later-than (FNLT) - Hard constraint % = (total # of incomplete tasks with hard constraints)/(total # of incomplete tasks) x 100 - The number of hard constraints should not exceed 5%	1	0 or 1
		51	Buffers should be inserted at the right places	0	0 or 1
e. Activity mis-assignments				2	
		52	No activity mis-assignments. There should not be any milestones/activity mis-assignn - Task mis-assignments (a task whose date has finished beyond the milestone to which it is assigned, or is associated with tasks or milestones which are not included in the file) - Orphan tasks (a task that has no association with a milestone, although it might be a successor or predecessor of other tasks)	1	0 or 1
		53	No empty milestones (a milestones that contains less than two tasks, ie zero or one	1	
f. Lag & Lead (negative lag)				2	
		54	Number of lags. The number of logic links with lag should be limited - number of logic links with a lag (lags) - Lag duration should not be greater than predecessor or successor activity duration	1	0 or 1
		55	No leads. Number of logic links with a lead (negative lag) (leads) should be zero	1	

Figure 4. Sample Project Checklist part #3.

SCHEDULE HEALTH ASSESSMENT / 3				
PROJECT:		PROGETTO ORATORIO IT		
START DATE		12/11/2013		
STATUS DATE		28/02/2014		
Schedule Health indicator	#	Detailed requirements specific requirements	total score	notes
4. Cost and resources requirements:			0	
a. Monetary value/cost of activities			0	
		<i>The assignment of monetary value to each activity should be made in accordance with the following rules:</i>		
	56	Monetary value of activities. Monetary value/cost of each activity should represent all/a reasonable amount for that work;	0	0 or 1
	57	Total monetary value. The monetary value/cost of the whole construction schedule should comply with the total contract amount; – The monetary value associated with an activity should play little role in constraining its duration;	0	0 or 1
	58	– The decision to include the cost of materials with the cost of their installation should be based on (a) whether or not the owner wants to reimburse for materials soon after they arrive at site and (b) the ratio of cost of materials to total activity cost; Progress payment requests should be reasonable and based upon scheduled activities which are in progress. – Cash flow front-end loading should be avoided.	0	
b. Project cost ratio			0	
	59	Project cost ratio range: Project critical path cost/total project cost should be within a min/max range	0	0 or 1
c. Resource loaded activities			0	
	60	Resource loading. A quality schedule should have resources assigned to every task (all task with durations greater than zero have resources, people or costs, assigned). – All tasks should be resource loaded – Missing resources% = (total # of incomplete tasks with missing resource)/(total # of incomplete task) x 100 – The resource-loaded schedule implies a correspondence with the average productivity used in the estimates.	0	0 or 1
	61	Resource productivity. The resources required to complete each activity, including their availability and productivity, should be considered to determine the duration of each activity, whether or not the resources are actually applied to activities in the schedule model.	0	0 or 1
	62	– The schedule should contain the most current resource estimates available Resource conflicts (i.e. people, places and things) should be analysed and mitigated – Schedule should be levelled – Congestion index (labor density 25-30 sqm/man) – Trades' peak resource loading – Trades' peak resource loading relation – Trades' rate of completion per week – Peak to average labor ratio	0	0 or 1
d. Project total level of effort			0	
	63	Total amount of working hours/days of project	0	0 or 1
	64	Project effort ratio (project critical path effort (number of laborens)/total project effort should be within a min/max range)	0	0 or 1
5. Control process requirements:			9	
a. Activity progress evaluation			2	
	65	Percentage complete. Assessing progress on an activity should make both the percentage complete and the expected real remaining duration consistent. – Duration-based percent complete should be compared with scope-based percent complete.	1	0 or 1
	66	Schedule slippage. In case of schedule slippage the entire path to which the lagging activities belong should be monitored (even if contains no-critical activity)	1	
b. Schedule review and baseline			2	
	67	Schedule maintenance. The schedule should be maintained/updated on a regular basis	1	0 or 1
	68	Actual progress must be compared to the baseline plan. – For every schedule change, logic, time and cost impacts should be assessed Variance report. Any variation that exceed predetermined user-defined threshold limits shall be reported.	0	
	69	– Easily modified and update variation should be tolerated – Bow wave analysis. Identify bow waves created by task owners "kicking the can", postponing and pushing tasks into the next status period.	1	
	70	Baseline execution index (BEI). BEI compares the cumulative number of tasks completed to the cumulative number of tasks with a baseline finish date on or before the current reporting period. – BEI = (total # of task complete)/(total # of tasks completed before now + total # of tasks missing baseline finish date) – BEI value should be greater than 1.00 – Historical versus forecast rate of accomplishment check to identify delta's between historical and forecasted completions.	0	0 or 1
c. Schedule projections			2	
	71	Schedule projections should be based on comparisons between what was planned and what actually happens.	1	0 or 1
	72	Corrective actions or changes must be approved and documented. – The interim schedule approval implies the acceptance of a practical and logical way to finish the remaining work on time. – The schedule output should be analyzed for variances and changes to the critical path and completion date	1	
d. Invalid dates and missed tasks			3	
	73	Invalid dates (invalid forecast / actual dates). Invalid dates are activity start and finish dates opposing to project status date (ie in the future or in the past). There should not be any invalid dates in the schedule. Missed Tasks. Tasks which are supposed to be completed already and the actual or forecast finish dates are after the baseline finish dates. The number of missed tasks should not exceed 5%. – Missed % = (total # of tasks with actual/forecast date past baseline date)/(# tasks with baseline finish dates on or before status date) x 100 – Task withouts baseline	1	0 or 1
	74		1	0 or 1
	75	Out of sequence logic errors and logic loops should be corrected.	1	0 or 1

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8th Nordic Conference on Construction Economics and Organization

Safety, space and structure quality requirements in construction scheduling

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Abstract

Quality assessment of a construction project schedule can be a challenging task for project stakeholders. A little research work has addressed quality of schedules though a good project schedule can be considered as one of the key factors of project success. The development of a reliable and easy to perform construction schedule quality assessment procedure seems to be a challenging task. Since Schedule Health Assessment of a construction project has to be strictly related to process requirements, it is used the 3 “S” rule as a starting point and framework for obtaining improved understanding of quality of construction schedules. The 3 “S” are Safety, Space and Structure, meaning that the planned process should provide a safe working environment to construction workers, sufficient space to perform construction activities and the required sequence of construction operations and project phases. The aim of the study is to implement a schedule quality assessment method that takes into account the 3“S” rule of construction process. The 3“S” requirements can be successfully integrated in a Schedule Health Assessment method, but to facilitate their implementation and control a flow-line chart is needed, thus the schedule tool becomes a new requirement for construction schedule quality control.

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Keywords: Construction management; Project Control; Project Scheduling; Quality; Safety.

1. Introduction

Construction planning, scheduling and controlling are main tasks of construction project managers. A good quality construction schedule does not assure project success achievement, but it can be a good path forward.

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A sound project schedule merge cost and technical data to influence project management decisions and actions. Several studies showed the impact of adequate planning on the eventual outcomes of construction project, and standards for good scheduling practice followed (Griffith, 2005, PMSC, 2007, GAO 2012).

Understanding the organization of the various materials, trades, and subcontractors in the project processes is an ability acquired only after years of study and experience (Callahan, Quackenbush, Rowings, 1992). Thus a tool to understand schedule quality during the scheduling process and to guide the scheduler to develop the final product, or to perform a quality control, can be a valuable instrument to enhance project performance.

The aim of the paper is to assess construction schedule quality through construction process-oriented quality requirements definition. Although a set of quality requirements of a project schedule can be easily defined by literature review and by scheduling standards, the development of a reliable and easy to perform construction schedule quality assessment procedure seems to be a challenging task. In a previous research by the authors a set of seventy five schedule quality requirements has been defined and a construction schedule quality assessment procedure was developed. This includes classification of schedule requirements in five groups termed as Schedule Health Indicators: general requirements, construction process, schedule mechanics, cost and resources, and control process. It is believed that construction process requirements play a major role in the quality assessment procedure, thus they need to be highlighted.

Concerning sound preparation of project schedule from the construction process viewpoint, a well-known rule-of-thumb for construction scheduling is the 3 “S” rule. The 3 “S” are Safety, Space and Structure, meaning that the planned process should provide a safe working environment to construction workers, sufficient space to perform construction activities and the required sequence of construction operations and project phases. These requirements are of capital importance for schedule effectivity. The present research work aims at implementing a Schedule Health Assessment Method that takes into account the 3“S” rule of construction process. The study is limited to the proper implementation of the 3“S” rule in scheduling process, without examining in depth other quality related scheduling features. In fact, many schedule characteristics should be checked in order to achieve a good quality level of the schedule and the 3“S” rule should not be considered without the others quality requirements. Another sub-aim of the paper is to integrate the 3“S” rule – related requirements in a framework of the five Schedule Health Assessment indicators previously defined. The research work first analyses the schedule quality problem, as approached by pertinent literature and standards, then the 3“S” rule for construction scheduling is examined in relation to the work of Callahan, Quackenbush and Rowings (1992) that first defined the 3“S” rule scheduling approach. It also addresses the seminal works of Kenley and Seppanen (2010) about Location-Based Management System for construction and of Akinci, Fisher, Levitt and Carlson (2002) who investigated time-space conflicts in construction projects.

The research method is based upon inductive reasoning. The study starts from time-space conflicts definition and, through detailed analysis of a sample project schedule, seeks to supply evidence of 3“S” rule importance for scheduling quality. The 3“S” requirements are then integrated in a more general Schedule Health Assessment Method. Sample project data are derived from a simple case-study of an existing building refurbishment project.

2. The schedule quality problem

Quality is the level of accomplishment of a product or a process to a set of performance requirements (ISO 9000:2005). Project success i.e. the achievement of project objectives is the main goal of project quality assessment. Griffith (2005) and the guide of the United States Government Accountability Office (GAO) report that there is a significant relationship between good scheduling practices used early in the project life cycle and the ultimate success of the project (GAO, 2009). Quality of the scheduling process and quality of the schedule itself can play an important role in the achievement of project success and represents a key process of construction project management.

Project scheduling has also an impact on safety (Larsen, Whyte, 2013, Saurin et alii, 2004). In Europe directive 92/57/EU (Temporary and mobile construction sites) requires an health and safety plan, and Suraji et al. (2001) found the planning and control failures related both to safety and production itself were major contributing factors to accidents in construction sites in the UK. In the U.S.A. Hinze (2002) has consistently found that pre-project and pre-task safety planning are among the critical measures required to achieve a zero accident target.

Quality of planning and scheduling process is addressed by several project management guidelines. The AACE International (AACE) Recommended Practice No. 14R-90 (2006) includes the "Schedule Quality Analysis", and the AACE Recommended Practice no. 48R-06 (2009) defines a guideline for schedule constructability review process of a construction schedule. The Practice Standard for Scheduling of the Project Management Institute (2007) describes the schedule development process and also a Conformance Index Assessment process to evaluate schedule quality.

The GAO "Schedule Assessment Guide" (2012), describes recommended best practices for project schedules and provides ten best practices associated with a high quality and reliable schedule. The US Defense Contract Management Agency (DCMA) has defined a 14 points metrics that supports the schedule analysis for assessing schedule quality. The National Defense Industrial Association (NDIA) published the "Planning and Scheduling Excellence Guide (PASEG)" that encompasses 10 quality control steps to validate the Integrated Master Schedule.

In addition to these standards and recommended practices, several researchers searched for a deeper understanding of quality and reasonableness of construction schedule. De La Garza et alii (1990) defined a subset of scheduling principles to enable construction schedule evaluation process for subsequent automation. Russell and Udaipurwala (2000) perspective on schedule quality assessment is related to construction strategy, "the plan of attack", plus the timing of activities. Zwikael and Globerson (2004) introduced a model for evaluating the quality of project planning called "Project Management Planning Quality (PMPQ)". Hietala (2009) indicated a framework to develop schedules with better quality and also to assess the quality of developed schedule. Moosavi and Moselhi (2012) defined a structured methodology to assist owners in the evaluation and approval of detailed schedule of contractors.

3. Safety, Space and Structure: 3 "S" rule for construction scheduling

Key element of construction schedule quality is the production model conceived in the schedule. Callahan et alii (1992) introduced the 3 "S" rule for construction planning and scheduling, meaning that the production model should address the safety of construction workers, should provide the required space for process operations and should follow the proper sequence of activities needed to build the construction product structures.

Good quality schedule logic includes considering safety of construction laborers as a main objective of construction operations. In fact the proper succession of activities is a primary requirement for a safe working place. It reflects the obvious limitation that the start of some activities, e.g. curtain wall construction, depends upon the completion of all, or part of, others (e.g. wall construction and scaffolding) to be completely executed and to be safe for construction workers. An example of limitation of space is that the work force on the activity being planned must both set and fit the space available and created to do the work (e.g. scaffoldings and building components or systems). The structure rule is due to physical or technological dependencies between construction activities (Callahan, Quackenbush, Rowings, 1992). An example of structure is that the curtain wall cannot be built until the supporting wall is erected and the steel sub-structure is fixed (Callahan, Murray Hons, 2011). This indeed it is strictly concerned with quality control of construction processes. While the "Structure" rule for network logic creation really is about the proper setting of dependencies between project activities, the "Safety" and the "Space" rules are really about time – space conflicts. The "Space" rule is concerned with space requirements for: crew (i.e. working space), equipment and temporary structure. Mainly it prevents contemporary use of the same space by different crews/activities. The "Safety" rule requires project scheduler to check safety problems due to errors in activity sequence that can affect safety of construction workers, and hazards created by working tasks in other space units.

All these issues can be addressed by Location-Based Planning (Kenley and Seppanen, 2010). In fact Location – Based management assumes that there is value in breaking a project down into smaller locations and using these to plan, analyses and control work as it flows through these locations. The location provides a container for project data at a scale which is easy to schedule and to control. The emphasis in location – based scheduling is to schedule the construction project achieving high level of productivity, quality and safety.

Once the project is decomposed into various locations, or space units, understanding the interactions between activities and spaces is needed. The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six type of spaces required by construction activities were detected:

1. Building component space;
2. Labor crew space;
3. Equipment space;
4. Hazard space;
5. Protected space;
6. Temporary structure space.

Each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur.

Time – space conflicts have three characteristics:

1. Temporal aspects of time-space conflicts: since activity space requirements change over time, time – space conflicts between activities only occur for certain periods of time.
2. Multiple types of time – space conflicts: depending on the types of space conflicting and the quantity of interfering spaces, time – space conflicts can have many types. Five major types of conflicts has been identified:
 - a. Safety hazard, when a hazard space generated by an activity conflicts with a labor crew space required by another activity.
 - b. Congestion, when a labor crew space or an equipment space required by an activity conflicts with another labor crew space, an equipment space, or a temporary structure or building component space required by another activity.
 - c. Design conflict, when a building component conflicts with another building component.
 - d. Damage conflict, when a labor crew space, an equipment space, or a hazard space required by an activity conflicts with the protected space required by another activity.
3. Multiple conflicts existing between a pair of conflicting activities, due to conflicts between multiple types of spaces required by two conflicting activities.

The problem is how to load these space requirements to a construction schedule. If this is done, project managers can use this information about time – space conflicts to modify their production models by changing construction methods, sequences and so forth to minimize problems related to time – space conflicts prior to construction. The main tool suggested by researchers and practitioners for time – space conflict resolution is the linear scheduling method, flow line or linear planning, integrated with a network model (Ciribini and Rigamonti, 1999; Kenley and Seppanen, 2010; Russell, Tran & Staub – French, 2014).

3.1. Sample application

A sample application of the 3 “S” rule to a construction schedule of a small refurbishment project is used to illustrate the problem. The activities of the energy retrofitting project of a residential four – storey building are: scaffolding, roof retrofitting, external wall insulation, base coat and wall finish, windows retrofit (table 1).

Table 1. Activity list of sample project.

Activity list / Space Units	Scaffolding		Roof retrofitting		External wall insulation		Base coat & wall finish		Win- dow retrofit	
		Days		Days		Days		Days		Days
SP0 – Ground floor	A – 0	2			C – 0	2	D – 0	1	E – 0	1
SP1 – First floor	A – 1	2			C – 1	2	D – 1	1	E – 1	2
SP2 – Second floor	A – 2	2			C – 2	2	D – 2	1	E – 2	2
SP3 – Third Floor	A – 3	2			C – 3	2	D – 3	1	E – 3	2
SP4 – Roof	A – 4	2	B- 4	5						

The first version of the construction schedule (fig.1 a and fig. 1 b) has some time - space conflicts and hazards spaces, because of the time overlapping of “D - base coat” and “E - windows retrofit” activities with “C - external wall insulation”, but has a very short total duration (fig. 1b). Note that the “A – scaffolding” activity and the “B – roof retrofitting” have been properly scheduled with no time – space conflicts.

The improved schedule (fig. 2), developed applying the test of the 3 “S” rule, is very different. The time – space conflicts of activities have been resolved, but the total duration is augmented. In particular, as the working space for the activities “C – External wall insulation”, “D - Base coat & wall finish” and “E – window retrofit” is the same, i.e. the building façade with the scaffolding system, the three activities have been sequenced with a finish – to – start relationship without any overlapping. This corrective action eliminated the hazard space created by the predecessor activities for the successor ones. Furthermore, to augment quality of finishes (activities D and E), the order of execution of working tasks in every space unit (floors) has been changed from bottom – up to top – down (figure 2 and 3). It is clear that only the integration between the two scheduling tools, the CPM network and the flow line chart can explain clearly the interactions between activities and space, thus highlighting possible time-space conflicts.

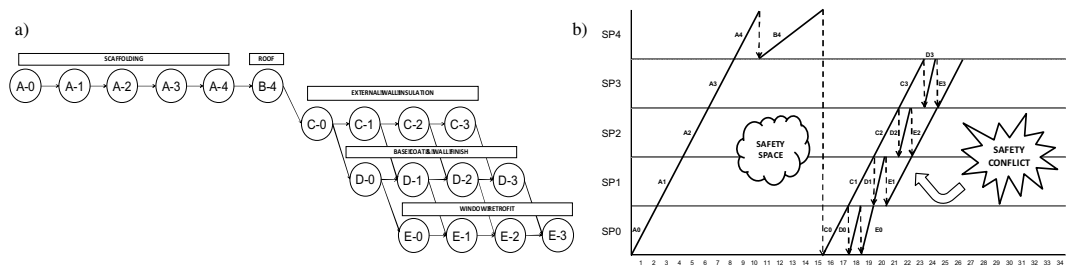


Fig. 1. Sample project schedule before 3 “S” analysis: (a) CPM schedule; (b) Flow Line schedule.

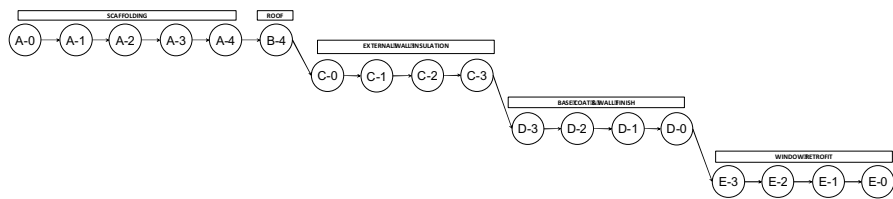


Fig. 2 . Sample project after 3 “S” analysis and correction: CPM schedule

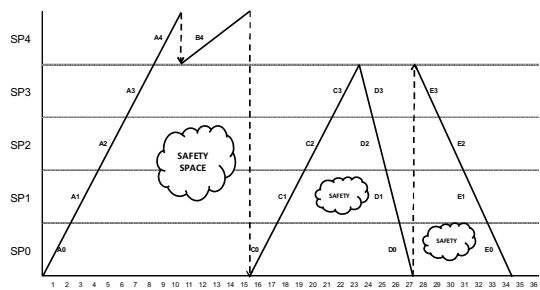


Fig. 3 . Sample project after 3 “S” analysis and correction: Flow Line schedule

4. Schedule Health Assessment & the 3 “S” rule

The problem of quality assessment of a construction schedule has been addressed through the definition of a set of related quality requirements as found in an ongoing research project (Bragadin, Kahkonen, 2014). The construction schedule quality requirements have been classified in five groups, thus defining five schedule performance indicators. This quality assessment process has been termed as “Schedule Health Assessment” and has the goal of quantifying schedule performance, thus enabling project team to implement a pro-active approach to construction scheduling. The 3 “S” rule of – thumb has been integrated in this evaluation process.

The Schedule Health Assessment method has also the aim of helping project managers and project schedulers to create a sound and reliable construction schedule. The method can be a valuable tool for auditing project scheduling process, and with this, construction project execution. A selected group of seventy five detailed requirements has been individuated and classified in five groups of requirements. This five groups of requirements were defined as Schedule Health Indicators. Each schedule indicator aims at defining a quality level of schedule performance in a specific topic to assess schedule health.

The five schedule health indicators are the following:

- 1. General requirements;
- 2. Construction process requirements;
- 3. Schedule mechanics requirements;
- 4. Cost and resources requirements;
- 5. Control process requirements.

Each Schedule Health Assessment Indicator is composed of the requirements as indicated in table 2 and 3, which, in turn, are composed by a subset of detailed requirements (Bragadin, Kahkonen, 2014).

Table 2. Schedule Health Indicators (part 1).

Schedule Health Indicator	Requirement
1. General Requirements	Schedule process procedure
	Schedule definition
	Activity definition
2. Construction process requirements	Activity sequencing & Structure adequacy
	Activity duration;
	Activity timing
	Construction process safety & productivity
3. Schedule mechanics requirements	Network and logic
	Critical path
	Float
	Soft & hard Constraints, buffers
	Activity mis-assignments
	Lag & lead (negative lag)

Indicator no.1 "General requirements" consists of a set of provisions that are aimed at conforming the schedule production process to quality standards related to the developing phase, to the schedule as a product, and to the contract requirements of the construction project. Indicator no. 2 "Construction process requirements" consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the execution phase of the construction project, i.e. to implement schedule constructability.

Indicator no. 3 "Schedule mechanics requirements" consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the networking technique for scheduling and monitoring the construction project. Indicator no. 4 "Cost and resources requirements" consists of a set of provisions that are aimed at verifying that the activities of the project, and the project itself, can be executed within the calculated time and budget. Indicator no. 5 "Control process requirements" consists of a set of provisions that are aimed at allowing an efficient project control process through the schedule updating and re-planning processes.

Table 3. Schedule Health Indicators (part 2)

Schedule Health Indicator	Requirement
4. Cost and resources requirements	Monetary value/cost of activities Project cost ratio Resource loaded activities Project total level of effort
5. Control process requirements	Activity progress evaluation; Schedule review and baseline; Schedule projections; Invalid dates and missed tasks.

As previously mentioned Indicator no. 2 "Construction process requirements" consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the execution phase of the construction project. Four are the basic requirements composing this indicator: Activity Sequencing; Activity Duration, Activity Timing and Construction Process Safety and Productivity (tab. 2). They are mainly concerned with schedule constructability (IPENZ, 2008). The activity Sequencing requirement aims at defining a construction-oriented network logic. Actually it matches very well with the "structure" part of the 3 "S" rule. The requirement "Construction Process Safety and Productivity" is related to safety and work efficiency of the construction site, and entails detailed requirements about work continuity, work flow of resources and time-space conflicts. It is really about construction project productivity improvement and health and safety. To be more specific the detailed requirements can be the following: safety / hazard space; non – congested work areas; work continuity; work flow (safe, orderly and organized).

As a result the 3 "S" rule-of-thumb fits very well with the Schedule Health Assessment proposed framework, though the integration process of the 3"S" in the schedule quality evaluation method requires, to be more efficient, the development of a flow-line chart of the schedule. Flow-line view of the network schedule becomes a key factor for quality checking concerning the Construction Process Indicator.

5. Conclusion

The success of a construction project depends in part on having a sound and good quality project schedule that defines when and how long work will occur and how each activity is related to the others.

Schedule quality can be pursued and checked with the Schedule Health Assessment method, which is the detection of schedule requirements satisfaction and the synthesis of the found results with five Schedule Health Indicators: general, construction process, schedule mechanics, cost and resources, control process.

In the present study construction process requirements has been focused because of their importance in effective schedule delivery. In particular the 3"S" rule, meaning safety, space and structure is believed to be an important guidance for project scheduler of construction projects.

The application of the 3"S" rule to a sample construction schedule has been performed thus highlighting its precious contribution to schedule efficiency survey. So safety, space and structure related requirements have been fully integrated in the Schedule Health Assessment method. Limitations of the research work are related to the

simple example used as case-study, it is felt that future testing on several construction project case-studies has to be performed to fully develop a complete testing and commissioning of the Schedule Health Assessment method integrated with the 3 “S” rule.

Flow – line view has revealed to be an irreplaceable tool for schedule health assessment, as the integration of the networking technique with the flow line chart highlights possible time-space conflicts. In fact 3”S” rule is mostly oriented to space usage in the building process and this enhances the need of a space – oriented scheduling tool. Thus the flow-line view of the activity network becomes another quality requirement of the construction project schedule.

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VI

Resource – Space Charts for Construction Work Space Scheduling

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Resource – Space Charts for Construction Workspace Scheduling

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Abstract

Construction production is typically highly dependent upon space to move, store and fabricate materials and building components, and to perform transformation and assembling activities. Construction planning and scheduling goal is to provide a logical order for activities taking into account safety, space and logic requirements. Construction process scheduling should also incorporate specific features of work-flows of project activities through work spaces. The Location-Based Management System (LBMS) is a recent and innovative method that aims at planning and managing construction projects in a process-oriented way, taking into account activity locations on-site. In an on-going research an improved scheduling method for construction operations has been developed, based on a CPM - Precedence Network plotted on a Resource–Space chart. Space Units of the project work are identified by a Location Breakdown Structure (LBS) like in the LBM System, and project activities are identified by a two dimensions coordinate system based on Resources (i.e. construction crews) and working Spaces (e.g. floors of a multi-storey building). As the Precedence Network is plotted on a resource – space chart, Space Units can be characterized by a maximum resource capacity number for each activity type, thus defining the available space capacity of working crews. In this way project scheduler can verify the quality of the produced schedule during the planning and scheduling process, as dimensions of workspaces and their congestion limits, safety spaces and protection spaces can be easily verified. The method has been tested on a sample project. The proposed scheduling approach can help unexperienced project schedulers to identify specific resource requirements for spaces needed for activities, and to define locations of these spaces and resources on building site. The proposed approach can be useful especially in case of project acceleration and time-cost trade-off, helping the project team to produce an efficient construction schedule.

Keywords: Construction, project scheduling, resource management, precedence network, workspace management.

1. Introduction

Construction projects are very specific industrial projects. One of the most important features of construction production is related to the building site. Building construction is an industrial activity in which workers build not only the product but also the working location, i.e. the building site. Therefore space for construction activities, including materials, machines and fabrication stations, traffic routes, places of construction work and welfare facilities must be designed, organised and planned (Riley, Sanvido, 1997). Construction planning and scheduling has the objective of providing a logical order for activities taking into account safety, space and logic requirements. In particular, it is believed that a construction schedule should focus on space requirements as they can have very important effects on safety and production quality (Akinci, Fischer, Levitt, Carlson, 2002; Ciribini, Galimberti, 2005). Understanding the organization of the various materials, trades, and subcontractors in the project processes is an ability acquired only after years of study and experience. Construction workspace is, at the same time one of the main components and constraints of construction scheduling, due to production context and building product characteristics. So, workspaces are generally difficult to proactively plan and manage, because of the dynamic nature of construction production where site layout and work environment change continuously as processes progresses. Workspaces are key elements of the process model embodied in a schedule, and work-space conflicts prevention is an important feature of a construction schedule. As standard planning and scheduling of a construction project can be achieved through networking techniques, the space – related component of the schedule is difficult to model and to efficiently take into account by an unexperienced project scheduler. Thus, a method to understand schedule workflow and spaces during the scheduling process can be a valuable instrument to achieve project success.

2. Literature review

Many scheduling methods have been proposed in literature in order to improve construction project workspace management with a scheduling model. As crews perform activities from a space unit of the project to another one, it might be advantageous to arrange for such crews to work continuously, without interruptions, thereby preventing idle intervals of equipment and manpower (Selinger, 1980). Riley and Sanvido (1995 and 1997) observed that current space planning in multi-storey building construction is limited to site layout and logistics, and they propose a space planning method that provides a logical order and priority for activities related to their needed spaces. Effectively a construction planner need to: (1) identify the space needed for activities; (2) define locations for these spaces on building floors; (3) develop a sequence of work that defines the order spaces are occupied; (4) identify potential spatial conflicts. Kang et alii (2001) observed that in a multiple repetitive construction project, construction cost and duration are dependent on: number of work areas, proper crew grouping, size of work areas, frequency of repetition of each activity, and provided an heuristic approach to allow optimal construction planning. Yang and Ioannou (2001) proposed a scheduling method with focus on practical concerns in repetitive projects, and implemented in particular the pulling effect in the continuity relationship between activities.

Yi, Lee and Choi (2002) presented a heuristic method for network construction and development for repetitive units project, with the aim of minimizing total project duration by reducing idle time of resources and spaces. Actually the heuristic changes the sequence with which crews complete the scope of work encompassed in each repetitive activity. This approach and general formulation has been applied in earlier and more accurate models (El Rayes and Moselhi, 1998) which guarantee a global optimum solution. Guo (2002) proposed to integrate computer-aided design with scheduling software for the dynamic identification of space conflicts on the jobsite. Work-space types are identified and time-space conflicts are studied. The seminal work of Akinici, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six type of spaces required by construction activities were detected and each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur. Ciribini and Galimberti (2005) observed that the H&S Management has widely to deal with working areas and space conflicts. A schedule model should indicate crew workflow directions, space requirements, and spatial buffers between activities. The optimization of the sequences of crews (workflows and production rates) can be done by scheduling work locations. Daewood and Mallasi (2006) and Mallasi (2006) observed that lack of execution pace planning may disrupt the progress of construction activities. Also, spatial congestion can severely reduce the productivity of workers sharing the same workspace, and may cause health and safety hazards to workers. A Critical Space-Time Analysis (CSA) approach is proposed to model and quantify workspace congestion and a computerized tool termed PECASO was developed for workspace management. The basic method suggested by researchers and practitioners for time – space project modeling is the linear scheduling method, flow line or linear planning, integrated with a network model (Kenley and Seppanen, 2010; Russell, Tran & Staub – French, 2014). Kenley and Seppänen (2009, 2010) observed that locations are important in construction because building can be seen as a discrete repetitive construction process, a series of physical locations in which work of variable type and quantity must be completed. They also observed that the location based methodology does not exclude Critical Path Method (CPM), in fact dependencies between activities in the various locations and between tasks (that are made up of activities of the same work item) are realized with CPM logic links. Construction projects are location – based projects (Kelley, Seppanen, 2010), where resources perform the same activity in different locations consecutively. Choy, Lee, Park et alii (2014), observe that current construction planning techniques have proven to be insufficient for work-space planning because they do not account for needed spaces of activities. So a framework for work-space planning is proposed categorizing activity spaces and including 4D Building Information Model (BIM) generation for space identification. Zhang, Teizer, Pradhananga and Eastman (2015) highlight safety and productivity poor performances of construction due to congested site conditions, and propose a method for automated visualization of workspace with BIM. Workspace modelling is based on five workspace sets and a conflict taxonomy.

In summary it is felt that there is a lack of structured planning and scheduling method for workspace management, at the design and schedule level of a construction projects. Workspace is an important concept and viewpoint for understanding characteristics of construction projects. The earlier research has covered already several important methodological characteristics of

construction planning and scheduling with the site space on focus. Although not covered explicitly here some research has covered also computerized assistance for the generation of alternative plans and schedules – for example (Kahkonen, 1994; Märki et al, 2007). The research presented in the following aims at proposing a method to understand work-space characteristics of a construction project for planning and scheduling purposes, thus creating a process-oriented environment for construction schedule production, and enabling high quality scheduling.

3. Proposed Method

3.1 REPNET: Repetitive Networking technique

In an on-going research an improved scheduling method for construction operations has been developed, based on a CPM - Precedence Network plotted on a Resource–Space chart termed Repetitive Networking Technique (REPNET). Locations or Space Units of the project are identified by a Location Breakdown Structure (LBS) like in the LBM System, and project activities are identified by a two dimensions coordinate system based on Resources (i.e. construction crews) and working Spaces (e.g. floors of a multi-storey building) (Bragadin 2010, Bragadin, Kahkonen 2011). As construction projects activities are often performed in many different locations of the building site by the same crew, a basic component of construction process understanding is the modeling of this time – space related process. A project activity performed in different locations, with similar sub-products, is termed repetitive activity. It is important that repetitive activities are planned in such a way as to enable timely movement of crews from one unit to the next, avoiding crew idle time and space - conflicts with other construction activities. The REPNET heuristics provide optimized activity scheduling maintaining the work continuity constraint and also the As-Soon-As-Possible total project duration calculation.

3.2 Resource-flow tracking with a resource – space chart

A Precedence Diagram Network of the repetitive project is plotted on a resource – space chart, with the x-axis representing resources and the y – axis representing space units of the project. The two coordinates identify each network node representing an activity performed in a specific space unit: the first coordinate is the main resource performing the activity (construction crew) and the second coordinate is the work space in which the activity is to be performed. The procedure of plotting the network on a resource – space coordinates has been used by many researchers in the past. In particular Yi, Lee and Choi (2002) presented an heuristic method for network construction and development for repetitive units project, with the aim of minimizing total project duration by reducing idle time of resources and spaces. The heuristic plotted the activity network on a Resource – Space Chart. Resources in the x-axis of the chart were the work crews or the equipment that was intended to perform activities. Resources were grouped by work item i.e. masonry, plastering, floor concrete slab etc. Multiple resources, i.e. multiple crews, were allowed for the same work item in order to perform parallel repetitive activities in different locations of the same task. In this way in every column of the chart activities are

grouped by resources (fig. 1). Space units of the project are plotted on the y-axis. Space units are the locations where only one crew can perform one activity at a time. In the proposed method the Location Breakdown Structure (LBS) can be displayed on the y-axis with a hierarchical decomposition of project locations (fig.3). An activity is defined as the set of construction operation performed by a specialized crew or equipment in a space unit of the construction project. In a repetitive construction project a set of activities, performed by the same crew in more than one space unit, is defined repetitive activity. Resources that perform a repetitive activity are identified by a j code. A task is defined as a set of repetitive activities performed by one or more than one crew for a work item, and is identified by the i code. So a resource path is completely identified as a repetitive activity by the ij code (ie resource path) and a single activity is identified by the ij-k code where k identifies the space unit where the activity is performed (i.e. space path, fig. 1). The k code is a unique alphanumeric character that identifies the operational space of the Location Breakdown Structure.

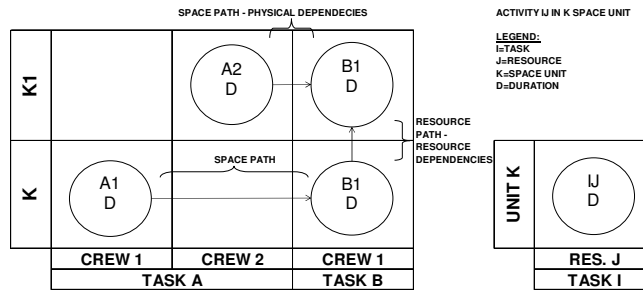


Figure 1: Network Diagram plotted on a Resource-Space Chart (adapted from Yi, Lee and Choi, 2002).

3.3 Space planning with the resource – space chart

The space identification for a construction schedule can be addressed by Location-Based Planning (Kenley and Seppanen, 2010). Location – Based management assumes that there is value in breaking a project down into smaller locations and using these to plan, to analyse and to control work as it flows through these locations. The location provides a container for project data at a scale which is easy to schedule and to control. The emphasis in location – based scheduling is to schedule the construction project achieving high level of productivity, quality and safety. The Location Breakdown Structure (LBS) is the backbone of this design process of on-site operations. Once the project is decomposed into various locations, or space units, understanding the interactions between activities and spaces is needed. In this phase the required spaces for each activity are detected and assigned to space units. Repetitive activities are decomposed into various activities to be performed into specific space units due to their production features, and single activities are allocated to specific spaces of the LBS. The sequence of activities is then generated using Precedence Diagramming Method (PDM). Activities are sequenced with network logic links and consecutive and concurrent work tasks are defined first for each space units and then for the complete building project. The prepared

activity network can now be plotted in the Space – Resource chart. The allocation of activity on the resource – space chart can highlight possible time/space conflicts between activities. Conflict resolution can be performed and the optimized space-allocated schedule can be completed. The flow-chart of the proposed scheduling process can be found in figure 2.

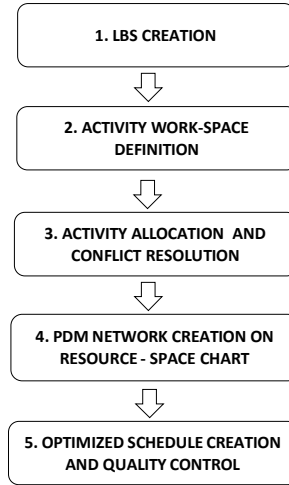


Figure 2: Proposed Scheduling Process.

The seminal work of Akinci, Fisher, Levitt and Carlson (2002) investigated the time-space conflicts in construction projects. Six type of spaces required by construction activities were detected: building component space; labor crew space; equipment space; hazard space; protected space; temporary structure space. Each construction activity requires at least one of these spaces. As activities can have time overlaps, i.e. they can be performed at the same time, time – space conflicts may occur (Akinci et alii, 2002; Mallasi, 2006; Zhang et alii, 2015). Time – space conflicts have three characteristics:

- Temporal aspects of time-space conflicts: since activity space requirements change over time, time – space conflicts between activities only occur for certain periods of time.
- Multiple types of time – space conflicts: depending on the types of space conflicting and the quantity of interfering spaces, time – space conflicts can have many types: safety hazard; congestion; design conflict; damage conflict.
- Multiple conflicts can exist between a pair of conflicting activities.

In the proposed method, four types of conflicts are identified for project scheduling purposes:

- Time / space conflicts due to activities' time-space overlapping and consequent contemporary space usage;

- Congestion of space due to labor density. The maximum number of workers per site location should be limited. The increase of labor density can lead to productivity loss and safety hazards.
- Safety hazards due to hazard spaces created by an activity for labor crew spaces of other activities.
- Damage conflicts due to labor crew spaces, equipment space, temporary structure space, hazard space required by an activity conflicts with a protected space of another activity.

The proposed resource – space chart based method can help project planner and production managers to avoid conflicts in many ways. In fact time-space conflicts can be avoided due to space allocation of activities in the resource-space chart. PDM activities plotted on the resource-space chart give a clear definition of the space used by labor crew for working. At the same time the layout space for each activity execution is identified on the chart, and it is easy to indicate the maximum number of workers per space units. Safety hazard spaces and protected spaces can be represented as unavailable spaces directly on the resource – space chart plotted for a specific time window. Basic limit of the proposed solution is the level of detail of the LBS, and the consequent space requirements for activities and representation of space conflicts between activities. The understanding of space conflicts needs a deep knowledge of the modelled construction process and proper level of detail of work packages.

4. Sample project

A sample project of construction of a small three storey residential building is presented. The created workflow model for the construction phase of the systems and interior finishing works is presented. The residential building of the sample project is composed by two edifices (A and B), joined by a covered corridor. Building A has three storeys while building B has only two storeys. The Location Breakdown Structure (LBS) is depicted in figure 3.

PROJECT	FLOOR	BUILDING	SPACE UNIT DESCRIPTION	SPACE UNIT LBS CODE
SAMPLE PROJECT -1	2 nd F-SECOND FLOOR: 1.SF	BUILDING A 2 nd F: 1.SF.A	FLAT-U6	1.SF.A.2
			FLAT-U5	1.SF.A.1
		BUILDING B 2 nd F: 1.SF.B	ROOF B	1.SF.B.1
	1 st F-FIRST FLOOR: 1.FF	BUILDING A 1 st F: 1.FF.A	FLAT-U2	1.FF.A.2
			FLAT-U1	1.FF.A.1
		BUILDING B 1 st F: 1.FF.B	FLAT-U4	1.FF.B.2
			FLAT-U3	1.FF.B.1
		ROOF C : 1.FF.C	ROOF C	1.FF.C.1
	GF-GROUND FLOOR: 1.GF	BUILDING A GF: 1.GF.A	CELLARS	1.GF.A.1
		BUILDING B GF: 1.GF.B	GARAGES	1.GF.B.1
		CORRIDOR: 1.GF.C	CORRIDOR	1.GF.C.1

Figure 3: Location Breakdown Structure of the sample project .

After the LBS creation work spaces of each activity have been defined, and the maximum number of workers per space unit has been assigned. Labour density limits are set with the aim

of satisfying technology and safety requirements. In figure 4 the maximum number of workers per space unit is shown. In this phase activity allocation on space units is performed with the aim of optimising construction processes in terms of work continuity of crews, safety issues, congestion avoidance due to contemporary space usage and protected spaces usage.

LBS			K	J	PARTITION W.	PLUMBING	ELECTRIC SYS.	CEMENT SCREED
A	U6	1.SF.A.2	8	4		3	3	4
	U5	1.SF.A.1	7			3	3	4
B	U4	1.FF.B.2	6	4		3	3	4
	U3	1.FF.B.1	5			3	3	4
A	U2	1.FF.A.2	4	4		3	3	4
	U1	1.FF.A.1	3			3	3	4
A	C	1.GF.A.1	2	2		3	2	2
B	G	1.GF.B.1	1			3	2	2
			K	J	I	H	G	F
					A	B	C	D

LEGEND:

MAX WORKERS NO.

N

Figure 4: Labour density limits per space unit of sample project .

At the end of this phase activity durations can be computed, as shown in table 1.

Table 1: Sample project activity data

TASK [i]:	A - PARTITION WALLS			B - PLUMBING			C - ELECTRICAL SYSTEM			D - CEMENT SCREED		
SPACE UNIT [k]	SPACE CAPACITY	No. Laborers	DUR. D	SPACE CAPACITY	No. Laborers	DUR. D	SPACE CAPACITY	No. Laborers	DUR. D	SPACE CAPACITY	No. Laborers	DUR. D
1	2	2	10	3	3	3	2	2	5	2	2	2
2				3	3	3	2	2	5	2	2	2
3	4	4	15	3	3	5	3	3	4	4	4	4
4				3	3	5	3	3	4	4	4	4
5	4	4	15	3	3	5	3	3	4	4	4	4
6				3	3	5	3	3	4	4	4	4
7	4	4	15	3	3	5	3	3	4	4	4	4
8				3	3	5	3	3	4	4	4	4

The creation of PDM network on basis of the Resource – Space chart (fig. 5) is easy to perform as a following step, as it is only needed to add logic links on the previous pattern of activity allocation on the LBS (fig. 4). The REPNET heuristics (Bragadin, Kahkonen, 2011) is then performed and a workflow optimised schedule is developed. In figure 6 the flow-line chart of the sample project is depicted. Then the produced schedule needs to be controlled. Firstly it is easy to observe that for the sample project the work continuity requirements has been satisfied almost completely, with the exception of activity D in units no.1 and 2. Also no time – space conflicts are detected and labour density requirement is satisfied (as activity durations were

computed with this constraint in table 1). For each working week the state of the project can be plotted, thus facilitating the controlling process through building site scheduled status representation. Completed and in progress activities are pointed out with successor spaces. Unavailable spaces because of cement screed hardening (after activity D implementation) are highlighted with different colour in the chart, to ease production management of successor construction processes (fig. 7).

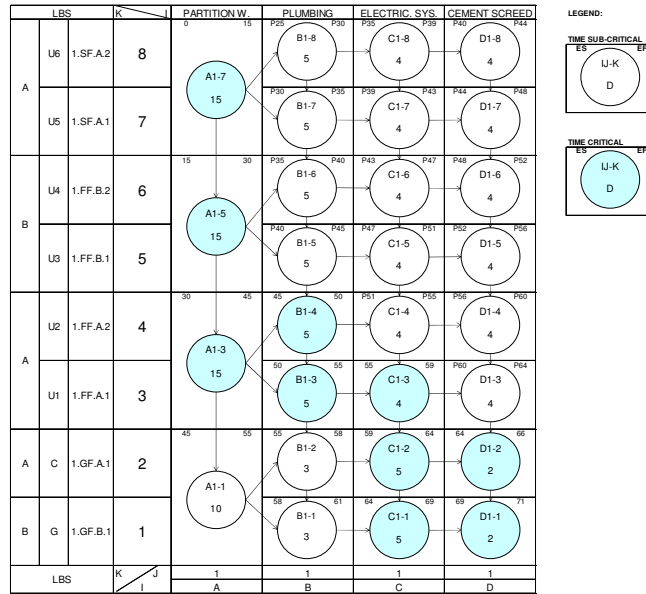


Figure 5: PDM network plotted on a resource – space chart - REPNET .

5. Discussion

The proposed method for construction scheduling, is based on workspace management issues. It is considered that the proposed simple method that uses resource – space charts can be useful for preparing schedules of good quality, meaning with this that they are process oriented and easy to update and maintain. On the other hand, the proposed method needs a skilled scheduler especially at the beginning, when LBS is created and activities' work spaces are defined. The need of developing a good LBS is because of the proposed scheduling method structure, i.e. the sharpness of LBS directly affects the sharpness of activities, as project activities are allocated into space units created in the LBS since the beginning. Mistakes and incongruences in this phase can affect schedule development and conflict detection. Also activity allocation and conflict resolution need a good construction expertise for a sharp modelling, but it is believed that the creation of the resource-space chart helps logic thinking and prearranged problem solving. Linking the proposed method with BIM models capturing location details of end product is an interesting way to develop it further. This would mean capturing directly the location data of interest from BIM model to be used for scheduling purpose. With the known spatial needs of different activity types and their operational resources this can provide grounds

for highly advanced and detailed scheduling solutions. As previously mentioned, limitations of the method can be found in the workspace modelling performed by the LBS and the two-dimensions resource-space chart. Detailed BIM models can be very effective for workspace conflict detection (Akinci et alii, 2002; Choi et alii, 2014; Ciribini, Galimberti, 2005; Dawood, Mallasi, 2006; Mallasi 2006; Zhang et alii, 2015), but it is also believed that a simple space modelling approach, as the one based on the LBS development, can be a quick and efficient method for workspace scheduling (Kenley, Seppanen, 2009, 2010; Russell, Tran, Staub-French, 2014).

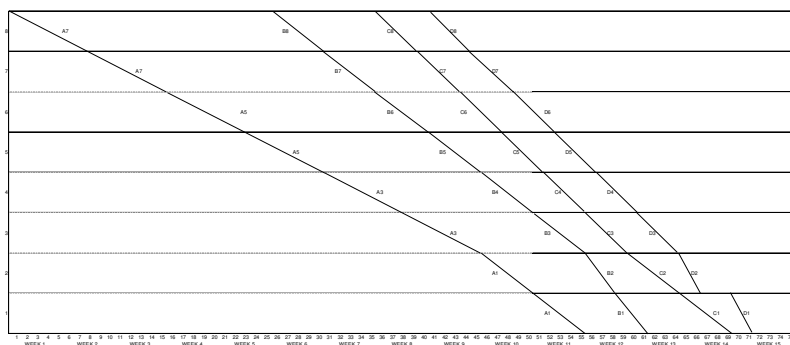


Figure 6: Sample project: flow-line diagram REPNET.

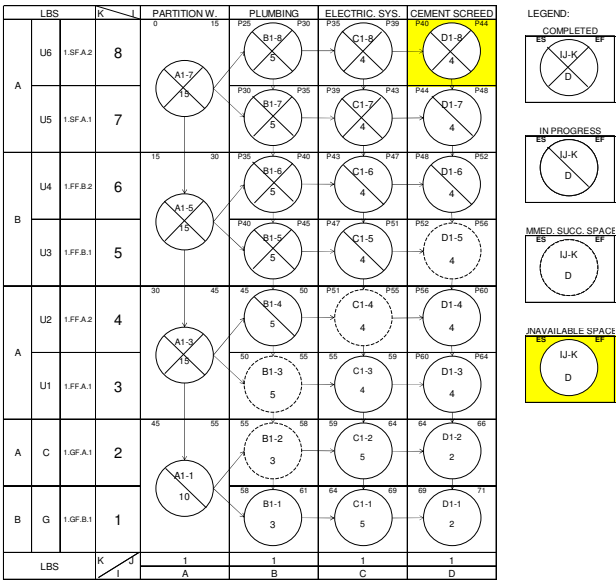


Figure 7. Sample project phase: week 10 plotted on a Resource – Space chart

6. Conclusions

The use of Resource-Space charts for construction workspace scheduling has been presented, since it is considered that explicit inclusion of spatial calculation is essential for preparing construction schedules of good quality. Many researchers and practitioners have highlighted the need of a workspace management system for construction process modelling, planning and scheduling. A Resource-Space chart, based on a Location Breakdown Structure, captures already main part of the logic of construction schedule. Thus, a PDM network can be easily prepared based on this. Accordingly project and production managers are creating process oriented project schedules where time – space conflicts of activities can be prevented, and congestion avoided due to the overall logic of the proposed scheduling method. The proposed method can be linked with BIM models for having direct access to spatial data.

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VII

A Planning and Scheduling Paradigm for Construction Strategy of a Building Rehabilitation Project

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A Planning and Scheduling Paradigm for Construction Strategy of a Building Rehabilitation Project

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Topic: Project construction and integrated system management

Abstract

Strategic decisions for a construction project play a fundamental role in the search for project success. The use of a process-based paradigm for planning and scheduling can help construction managers to create different production scenarios to choose the more suitable strategy for a building construction project. Rehabilitation construction projects have some specific features. First of all the existing building creates a spatial constraint for building activities, in terms of accessibility and layout of working placement, i.e. space for construction operations, and in terms of transportation of building materials and transportation and use of machines and equipment. On the other hand, the possibility of contemporary or overlapping construction operations, because of the structure of the locations of the building, can give flexibility to the planning of activities, i.e. different alternatives for the sequence of the operations. Construction project managers need to simulate with precision and realism the construction process to create these different scenarios, with the aim of optimizing production processes as to reach project objectives. This task can be accomplished through a planning and scheduling paradigm based upon the project Location Breakdown Structure (LBS) and the Precedence Diagramming networking technique plotted on a resource – space chart. A case study of an existing building rehabilitation project has been used to compare the project schedule prepared by the owner for the bid phase and the different scenarios created by the company for the construction phase. The proposed planning and scheduling paradigm can be used to optimize the construction strategy, especially in building rehabilitation projects where multiple choices for activity sequencing are possible. Future research work will entail the evaluation of the quality of the schedule created with the proposed method.

1. Introduction

A typical hierarchical structure of the scheduling process is composed by a master schedule and safety oriented schedule, both developed by the owner's consultants, (designers and safety coordinator in Europe), and a detailed schedule developed by the general contractor.

The detailed schedule developed by the contractor is a multiple-task document. Firstly has the task of demonstrating to the owner how the construction company will accomplish design and contract requirements for construction process in terms of total project duration, sequence of activities, resource loading of construction tasks, and cost/price loading of project phases. Secondly it has to satisfy safety requirements included in the owner's safety plan, i.e. in the safety oriented schedule.

Last, but not least, the detailed schedule entails the contractor's strategy of the construction process, the "plan of attack" (Russell, Tran, Staub-French, 2014) for the execution phase.

Strategic decisions for a construction project play a fundamental role in the search for project success. The use of a process-based paradigm for planning and scheduling can help construction managers to create different production scenarios to choose the more suitable strategy for the building construction project. In rehabilitation construction projects, multiple project work scenarios are possible because of the existing building structure which creates different work areas.

Rehabilitation construction projects have, indeed, some specific features. First of all the existing building creates a spatial constraint for building activities, in terms of accessibility and layout of working placement, i.e. space for construction operations, and in terms of transportation of building materials and transportation and use of machines and equipment. On the other hand, the possibility of contemporary or overlapping construction operations, because of the structure of the locations of the building, can give flexibility to the planning of activities, i.e. different alternatives for the sequence of the operations.

A resource-based paradigm for construction project detailed planning is proposed for the construction strategy definition performed by the contractor's production / construction managers.

2. Literature review

Many scheduling methods have been proposed by researchers in order to improve process-oriented construction scheduling through the development of a scheduling model. Construction projects are location – based projects (Kenley, Seppanen, 2009, 2010), where resources, i.e. construction crews, perform the same building activity consecutively in different locations, i.e. the space units, for most of the time of the building process. Therefore, a process oriented scheduling model should entail these two components, resources and space, to individuate activities and their sequencing.

The basic method suggested by researchers and practitioners for time – space project modeling is the linear scheduling method, flow line or linear planning, integrated with a network model (Kenley and Seppanen, 2010; Russell, Tran & Staub – French, 2014). Russell and Wong (1993) described the development and use of a new generation of planning structures to model repetitive construction projects. An integrate construction project management system called Representing Construction has been implemented, based on a CPM – based network and time algorithm and several graphic representations of repetitive activities through flow – lines charts. Kahkonen (1994) developed a scheduling model, which focus on the logic of building construction and activity dependencies. Main causes of activity dependencies in construction projects are due to resource types and work-area structure. The developed scheduling model aims at support strategic and early planning decisions and the systematic preparation of construction schedules. Riley and Sanvido (1997) proposed a space planning method that provides a logical order and priority for activities related to their needed spaces. El-Rayes and Mosehli (1998) suggested that resource – driven scheduling accounts directly for crew work continuity and facilitate effective resource utilization. Harris and Ioannou (1998) created the scheduling repetitive model that ensures continuous resource utilization with a flow view and a PDM view of the model. Arditi, Tokdemir and Suh (2001, 2002) integrated non – linear and discrete activities into LOB calculations and defined time and space interdependencies among activities as a base concept for repetitive project scheduling. Yi, Lee and Choi (2002) presented a heuristic method for network construction and development for repetitive units project, with the aim of minimizing total project duration by reducing idle time of resources and spaces. Ciribini and Galimberti (2005) observed that the H&S Management has widely to deal with working areas and space conflicts. A schedule model should indicate crew workflow directions, space requirements, and spatial buffers between activities. The optimization of the sequences of crews (workflows and production rates) can be done by scheduling work locations. Kenley and Seppänen (2009, 2010) observed that locations are important in construction because building can be seen as a discrete repetitive construction process, a series of physical locations in which work of variable type and quantity must be completed. Russell et alii (2014) examined how construction strategy selection can help construction managers. Different strategies can be developed and compared with linear planning and scheduling. Linear planning is believed to add value to strategy definition of repetitive construction projects, but CPM logic links are necessary to identify activity sequencing.

3. The REPNET approach for construction scheduling

In an on-going research an improved scheduling method for construction operations has been developed, based on a Precedence Diagram Network plotted on a Resource–Space chart termed Repetitive Networking Technique (REPNET) (Bragadin 2010, Bragadin, Kahkonen 2011). Locations or Space Units of the project are identified by a Location Breakdown Structure (LBS), and project activities are identified by a two

dimensions coordinate system based on Resources (i.e. construction crews) and working Spaces as identified by the LBS (e.g. floors of a multi-storey building). An activity is defined as the set of construction operation performed by a specialized crew or equipment in a space unit of the construction project. In a repetitive-based construction project a set of activities, performed by the same crew in more than one space unit, is defined repetitive activity. Resources that perform a repetitive activity are identified by a j code plotted on the x-axis. A task is defined as a set of repetitive activities performed by one or more than one crew for a work item, and is identified by the i code. So a resource path is identified as a repetitive activity by the ij code and a single activity is identified by the ij-k code where k identifies the space unit where one crew at a time only (figure 1) performs activity. The k code is a unique alphanumeric character that identifies the operational space of the LBS, and space units are plotted on the y-axis.

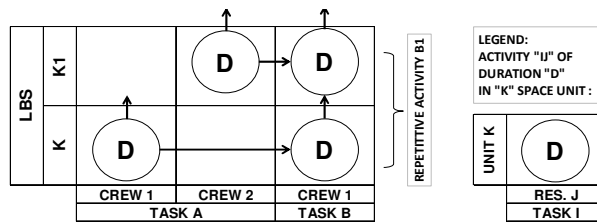


Figure 1: Network Diagram plotted on a Resource-Space Chart.

4. Project strategy and scheduling process for construction

Project Strategy is a comprehensive definition of how a project will be developed and managed (APM, 2006). Artto, Kujala, Dietrich and Martinsuo (2008) define Project Strategy as the direction in a project that contributes to success of the project in its environment. Strategy is not a plan (Patanakul, Shenhar, 2012). Each project must have a plan and a schedule for executing, but strategy is not a plan, it is at a higher level. Once the strategy has been established, plans and schedules include the tactical decisions about activities that should be carried out, and involve resources, timelines and deliverables. A good strategy involves both effectiveness and efficiency. A project strategy will include the “why”, the “what” and the “how” to create the best competitive advantage and value from the project. Patanakul and Shenhar proposed the following definition of project strategy: the project perspective, position, and guidelines for what to do and how to do it, to achieve the highest competitive advantage and the best value from the project.

Russell et al. (2014) defines project strategy for a construction project basing on its characterization in terms of time and space. Time represents discrete points of execution phase and between them a “strategy mode”, i.e. a strategy approach is

implemented. Space is made of spatial elements in the project's spatial system that represent a set of locations that constitute all or part of a sub-project, or a subdivision into functional areas or work zones. Thus a spatial element can be represented in hierarchical terms, and a Location Breakdown Structure can be defined for the project. Russell et al. (2014) give the following notion of construction strategy: "a strategy for constructing a spatial / system element of a project consists of an approach comprised of a strategy mode and the means for achieving it in the form of specific tactical variables and accompanying values, selected in response to client or contractor objectives and project constraints and conditions, as of a specific point in time".

Three are the fundamental strategy modes: normal duration delivery; accelerated delivery and phased delivery. Tactical variables can be defined at a project level or at a spatial / system level, and entails site project management staffing, communication/information management and building site layout organization and facilities. At a spatial level the most important variables are: resource type and availability; production rates; workflow and sequencing; materials and equipment handling and transport. Construction project constraints entail contractual constraints, environmental, regulatory, technology constraints and stakeholder, capacity, availability and information constraints.

Therefore, project strategy can be mainly developed through the project schedule. In the Italian construction sector the general approach to project scheduling basically follows Public Works regulation. Thus, the development of a project schedule is achieved through three different levels of detail.

First the owner's consultant, designer or project manager, creates a project plan which has the specific task of computing the total project duration for contract purposes, the master schedule. The master schedule is based upon "big" work packages which basically coincide with work categories of subcontractors. In Italy the law applicable for public works, the Code of Contracts ("Codice dei Contratti"), identifies this schedule as the design-based schedule ("Cronoprogramma di Progetto").

Second, the owner's safety consultant develop the safety-oriented construction schedule. The well known European Directive 92/57/UE on construction safety has introduced the safety coordinator, a professional which has the task, in the design phase, of designing the building site safety, and in the execution phase of coordinating and controlling health and safety provisions and actions. As construction works' safety can be implemented mainly through construction planning and scheduling, an important component of the owner's safety plan (i.e. "Piano di Sicurezza e Coordinamento") developed by the safety coordinator in the design phase is the safety-oriented project schedule ("Cronoprogramma dei Lavori"). The owner's safety-oriented project schedule sets the safety requirements of the building project that must be satisfied by construction process. Generally, to avoid confusion and misunderstandings, the safety-oriented schedule become the owner's schedule in the design and bidding phase.

Then, the general contractor develops the detailed schedule ("Programma Esecutivo Dettagliato"), and submit it to the owner's works supervisor ("Direttore dei Lavori") before the commencement of works on site.

It is of evidence that these three different levels of planning and scheduling entail different project strategies, on the owner's side or on the contractor's side. The design-based owner's schedule has the task of demonstrating the feasibility of the designed works in the terms of the contract. In particular, it has to show the economic commitment of the two parts, owner and contractor, for work in progress payments related to project deliverables/status. The safety-oriented project schedule has the task of representing the safety strategy entailed in the coordinator safety plan and in design contract documents. Only the detailed schedule can entail contractor's choices about building construction process, and it is in this document that actual project "process-based" strategy can be included.

5. Case Study: rehabilitation building construction project strategy

Strategic decisions for a construction project play a fundamental role in the search for project success. The use of a process-based paradigm for planning and scheduling can help construction managers to create different production scenarios to choose the more suitable strategy for a building construction project. Therefore, construction project managers need to simulate with realism the construction process to create different scenarios defined by different strategies, with the aim of optimizing production processes as to reach project objectives. This task can be accomplished through the proposed planning and scheduling paradigm (REPNET) based upon the Location Breakdown Structure (LBS) and the Precedence Diagramming network plotted on a resource – space chart. A case study of an existing building rehabilitation project has been used to compare the project schedule prepared by the owner for the bid phase and the different scenarios created by the company for the construction phase.

An excerpt of the owner's schedule can be found in figure 2. Only the demolition and structural reinforcement phases are represented in the bar chart schedule, developed with MS Project®. Project activities are planned in a sequence which is regardless of actual work areas, with few overlapping activities. The project strategy mode is "phased delivery" with normal duration, as one single crew can perform most of the activities. The contractor can plan and schedule different scenarios, coinciding with different approaches to project execution. Project strategy mode is "accelerated delivery". The first step is the definition of a Location Breakdown Structure (figure 3). The second step is the study of the acceleration of the project thorough multiple crews loading on activities. Thus it is possible to overlap activities, also because of different work areas created by different floors and space units of the building. Work safety requirements can be satisfied because the different work areas of activities creates no safety work-space conflicts and congestion. In the case study, two are the suggested project strategies, and basically they optimize the workflow sequence through building spaces with multiple crews loading. Four crews are loaded on project phase and each one perform three repetitive activities. The activity durations of the original schedule

were kept as constants. The activity list of the demolition and structural reinforcing phases can be found in table 1.

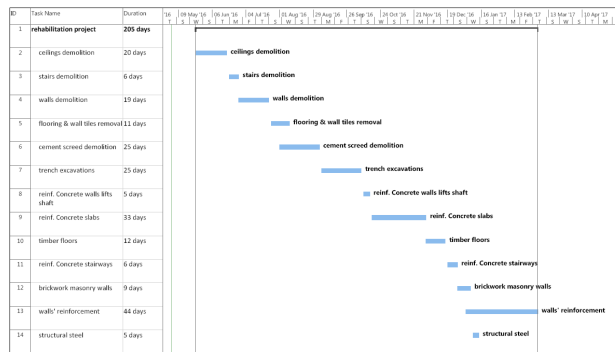


Figure 2: Original schedule, demolition and structural reinforcement phase (MS Project ®).

PROJECT	FLOOR	SPACE UNIT DESCRIPTION	SPACE UNIT LBS CODE	SPACE UNIT ID
BUILDING REHABILITATION PROJECT	ROOF: 1.RO	AREA B	1.RO.B	10
		AREA A	1.RO.A	9
	1 st -FIRST FLOOR: 1.FF	AREA B	1.FF.B	8
		AREA A	1.FF.A	7
	GF-GROUND FLOOR: 1.GF	AREA B	1.GF.B	6
		AREA A	1.GF.A	5
	UG-UNDERGROUND FLOOR:	AREA B	1.UG.B	4
		AREA A	1.UG.A	3
	ST-STAIRCASES: 1.ST	STAIRS B	1.ST.B	2
		STAIRS A	1.ST.A	1

Figure 3: Location Breakdown Structure of the case study

ID	ACTIVITY DESCRIPTION	DURATION ORIGINAL SCHED.	DURATION OF ACTIVITIES IN WORKING AREAS							
			1-2	3	4	5	6	7	8	
A	CEILINGS DEMOLITION	20				4	4	6	6	
B	STAIRS & WALLS DEMOLITION	25	6	1	1	4	4	4	5	
C	FLOORING AND WALL TILES REMOVAL	11				2	3	3	3	
D	CEMENT SCREED DEMOLITION	25				4	5	7	9	
E	TRENCH EXCAVATIONS	25		5	6	7	7			
F	REINFORCED CONCRETE WALLS OF LIFT SHAFT	5				3		2		
G	REINFORCED CONCRETE SLAB	33		4	4	6	7	6	6	
H	TIMBER FLOORS	12	12							
I	REINFORCED CONCRETE STAIRWAYS	6	6							
L	BRICKWORK MASONRY WALLS	9		1		1	2	2	3	
M	REINFORCEMENT OF BRICK MASONRY	44	4	10	10	5	5	5	5	
N	STRUCTURAL STEEL	5		1		1	1	1	1	

Table 1: activity list of demolition and reinforcing phases the case study

In the first scenario (1) resource paths start from the first floor of the building (figure 4-5). This strategy develops a total duration of the two phases of 106 days versus the 205 days of the original schedule (figure 2). In the second scenario (2) the commencement of activities is located in the ground floor, and the two phases' completion can be reached in 89 days (figure 6-7). It should be noted that project

acceleration is achieved through multiple-crew loading on activity performed in different work areas.

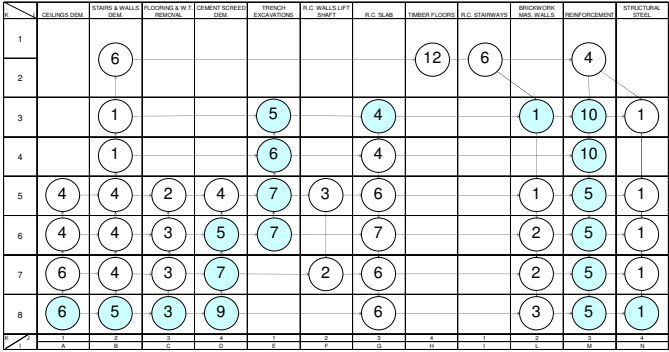


Fig. 4: Resource – Space Chart of the case study scenario 1

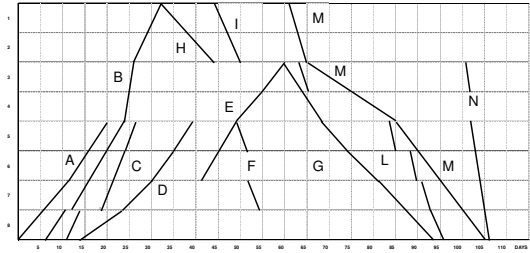


Fig. 5: Flow-line of the case study scenario 1

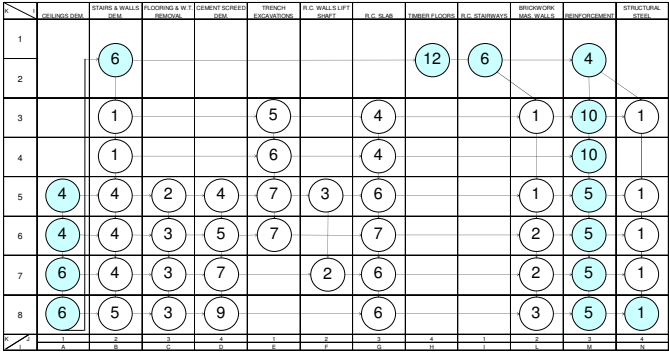


Fig. 6: Resource – Space Chart of the case study scenario 2

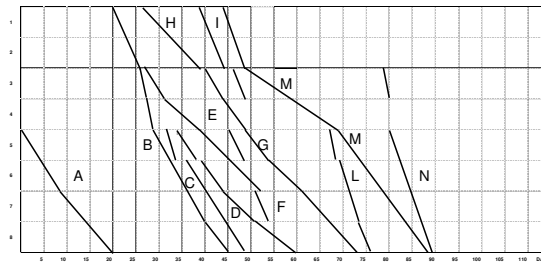


Fig. 7: Flow-line of the case study scenario 2

6. Conclusions

Despite project acceleration cost and benefit analysis, that is still to be performed, it is of evidence that process-oriented scheduling through PDM network plotted on a resource-space chart can display in-deep insight of the construction process strategy. Construction strategy related decisions are fundamental components of construction project management. Construction managers can use the proposed planning and scheduling method with the aim of creating different project execution scenarios. A case study of a building rehabilitation project has been used to test the proposed approach and to present its results. Rehabilitation construction projects usually have specific features and constraints to the production process in terms of space availability and working areas because of the existing building structure, but also can have multiple degrees of freedom in terms of activity sequencing and work-flow management. The REPNET approach seems to be suitable to model rehabilitation construction projects if they actually have a repetitive “nature”. Future research work will entail the evaluation of the quality of the schedule created with the proposed method.

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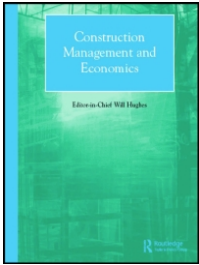
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VIII

Schedule Health Assessment of Construction Projects

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Schedule health assessment of construction projects

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Several factors can contribute to the success of construction projects. A sound and good quality construction schedule is considered to be one of them. The quality of schedules has been a research topic only for a few efforts and amongst them construction-oriented research is even more rare. Methodical grounds for assessing schedule quality have been studied via literature study for the development of appropriate solutions to assess the quality of construction schedules. These findings combined with the experiences from practical implementations have resulted in the definition of a metric to measure schedule quality for construction projects. It includes 75 schedule requirements classified into 5 groups: general requirements, construction process, schedule mechanics, cost and resources and control process. This structure forms a core for the developed method to assess construction schedule quality termed as Schedule Health Assessment. The developed method has also the purpose of assisting project planners to produce and maintain good quality schedules starting from the project initiation until its completion, as via using the method to detect deficiencies of project schedules and other critical issues having importance with respect to schedule maintenance.

Keywords: Critical path method, project control, quality, scheduling.

Introduction

Construction projects are generally complex endeavours, and project planning is an essential management function to guide construction project implementation, starting from the early design phase until project execution on site. Planning is a process of forecasting future events and outcomes that may be uncertain or even unknown. It means assessing the future and making provisions for it by gathering facts and opinions, in order to formulate an appropriate course of action (Uher, 2003). Project schedule is an important output of planning. Basically it explains the sequence of operations together with calendar dates and logic links between activities. Furthermore, a well-elaborated project schedule and model behind it can explain the dynamics of the project and can provide means for various analyses, project control and co-operation with project partners. Generally, the purpose of scheduling is to provide a guide that represents how and when the project will deliver the products defined in the project scope and by the project team (Project Management Institute, 2007).

Several factors can contribute to construction project success, and the schedule quality is considered to be one of them. A sound project schedule can be helpful in managing construction production with the purpose of improving productivity and quality through better planning and control. A good quality project schedule merges cost and technical data to support project management decision and actions, so project managers and stakeholders have to use project scheduling to understand project status and the probable development of future project activities. (Kenley, 2014; Isaac and Navon, 2014) Therefore, a good quality project schedule can be very important in the selection of an appropriate project organization form and of construction strategy (Russell *et al.*, 2014). Griffith (2005) and the guide of the United States Government Accountability Office (GAO) report that there is a significant relationship between good scheduling practices used early in the project life cycle and the ultimate success of the project (United States Government Accountability Office, 2009). It looks obvious that the quality of the scheduling process and quality of the schedule itself can play an important role in the achievement of project

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success. Schedule quality survey can be thought as a key process of construction project management and an indicator of overall process quality (Zwikael and Globerson, 2004).

On the other hand, the quality of construction schedules in particular has been researched in a rather limited manner. Previous research efforts that have addressed the content of schedule quality and its control with a direct approach, meaning with this an approach for a project control procedure, where the main attention is on the schedule audit with a contract management viewpoint, i.e. they have had a legal connotation and focus on contractual aspects, not on building site process (De La Garza, 1990; Moosavi and Moselhi, 2014). Obviously the quality of schedules, in general, has been always addressed in textbooks and scientific papers concerning construction project planning and scheduling methods and tools (Harris, 1978; Callahan *et al.*, 1992; Gantt, 1913; O'Brian and Plotnick, 2006), and some industrial standards exist which cover procedures to achieve schedule quality, but most of those standards are outside construction context. Since construction projects can be considered as complex endeavours, and construction scheduling as process requiring then specific skills and competences, we are seeing this interplay as an object where a method for schedule quality assessment, or schedule quality evaluation can be beneficial for guiding the scheduling process. The leading idea is to create a pro-active method to develop and check the produced schedule. With this goal in mind, a set of quality requirements applicable to construction schedules have been identified through pertinent literature and by exploring existing standards, and a metric to measure schedule quality is proposed for the purpose. The measurement system is based upon five key performance indicators (KPIs), termed Schedule Health Indicators, derived from a categorization of the selected schedule requirements.

Previous work

Relevant information and data contained in a construction schedule require a proper reviewing process. O'Brian and Plotnick (2006) describe the reviewing process of a submitted CPM construction schedule with a legal accountability approach. In particular, legal aspects are highlighted related to the consequences of the review process and to the rights of each part of the signed contract. After this, five major components of a good quality schedule are indicated: scheduling software; activity characteristics; network complexity; construction logic; dates and calendars. Each of these five major components focus on specific check points

or system requirements. Twenty-four detailed check points are described. The aim of the review process is not to verify that the contractor can perform the contract work according to the plan of execution provided by the CPM, but that the project schedule is technically correct, and that logic and durations appear 'reasonable'.

Principles and characteristics of a quality-oriented scheduling process and of a quality schedule were also detected by De La Garza *et al.* (1990) and De La Garza (1990). The study individuates three stages of the scheduling process which are needed for schedule analysis and validation:

- prior to the start of construction;
- during project execution;
- at project completion.

In each of these stages a validation of the schedule is needed. The validation can be conducted by owners and contractors, and Project Managers and Schedulers need to check if the schedule meets the requested efficiency requirements. The validation process prior to the start of construction entails the check of the following schedule characteristics: contract requirements; participation of major subcontractors; inclusion of special construction-oriented activities; critical path and overall degree of schedule criticality. The validation process during project execution entails: project control; schedule maintenance; detection of 'in trouble' activities. The research does not address the third phase validation. An automated system called CRITEX, written for the US Corps of Engineers has the purpose of 'critiquing' construction schedules from four perspectives: general requirements, logic, cost and time of the project and of the activities. The system also encompasses 34 provisions for schedule quality assessment.

The contract management approach of O'Brian and Plotnick (2006), and of De La Garza *et al.* (1990) is believed to be a limit of the proposed schedule reviewing process.

Starting from these two main references, research-based understanding of construction schedule quality has revealed three main research categories: characteristic of scheduling process, quality of scheduling process and quality of schedules.

Characteristic of scheduling process is related to scheduling methods, rules and approach, focusing on the development of industrial standards about the scheduling function. A trustable scheduling process is about quality specifications of the production process for construction schedules, and schedule quality concerns the level of performance needed by a construction schedule (seen as a product).

Characteristic of scheduling process

An industrial survey of CPM scheduling use in US Construction Industry by Galloway (2005), revealed a remarkable need for standards in construction project scheduling.

Concerning industrial guidelines for project scheduling the first edition of the Project Management Institute 'A Guide to the Project Management Body of Knowledge' (1996), defines the Knowledge Area of 'Project Time Management' as a subset of Project Management that includes the processes required to ensure timely completion of the project. Project Schedule is simply defined as 'the planned dates for performing activities and the planned dates for meeting milestones'. Also the IPMA Competence Baseline (2006) includes in the Technical Competence elements the 'Time & Project phases', which entails a description of the possible process steps with a clear reference to the use of 'Critical Path Diagrams'. More recently, the APM Competence Framework of the Association for Project Management (2015) defines Schedule Management as 'the process of developing and maintaining schedules for the work activities required to implement a change initiative'.

The 'Practice Standard for Scheduling' of the Project Management Institute (2007) confirms that a key to project success is to apply knowledge, experience and intuition to a project plan and the attempt to execute according to the plan. Scheduling is one of the basic requirements of project management planning and strategic analysis, and has the purpose of providing a 'roadmap' that represents how and when the project will deliver the products defined in the project scope. This can be achieved thorough a 'Schedule Model' (Project Management Institute, 2007), a dynamic representation of the project's plan for executing the project's activities, developed by the project team's applying the scheduling method to a scheduling tool using project-specific data such as activity lists and activity attributes. A scheduling method is a system of practices, techniques, procedures and rules used by project schedulers and performed either manually or with a project management software, i.e. a scheduling tool which provides schedule components supporting the application of a scheduling method (Project Management Institute, 2007). The Schedule development process includes selecting a scheduling method and tool, incorporating project-specific data within that scheduling tool to develop a project-specific schedule model and generating project schedule. This process has the aim of producing a schedule model of project execution, which has to be regularly updated to reflect progress and changes. Scheduling process includes activity definition, activity sequencing, activity resource

estimating, activity duration estimating, schedule development and schedule control (Project Management Institute, 2007).

The AACE International (AACE) Recommended Practice No. 14R-90 (Douglas, 2006) describes the roles and responsibilities of a Planning and Scheduling Professional during the various phases of project planning and schedule development, management and control, also establishing planning and scheduling guidelines for training and professional development. Scheduling is defined as the 'process of converting a general outline plan for a project into a time-based schedule based on available resources and time constraints'.

The GAO 'Cost Estimating and Assessment Guide' (2009), describes recommended best practices for developing and managing capital programme costs of projects using public funds. The guide focuses on project cost estimating, planning and managing. The GAO guide includes between major reasons of project success the quality of its schedule. Schedule provides a time sequence for the duration of project activities, and should integrate the logical relationship between activities, activity resources requirements and durations, and any constraint that affect their start and completion. The GAO guide indicates nine requirements useful to develop and maintain an integrated network schedule.

The CEN Workshop Agreement CWA 16022 (2009) 'Project Schedule and Cost Performance Management', (PSCPM) gives specific indications on the informative system entailed in project scheduling function.

Quality of scheduling process

Quality identification of scheduling process aims at developing the schedule production process in a way that the final product (the schedule) will have a set of inherent characteristics that will fulfil project requirements (ISO, 2005). The intended functionality of the schedule should be validated during the course of the project (De La Garza, 1990; De La Garza *et al.*, 1990).

Zwikael and Globerson (2004) introduced a model for evaluating the quality of project planning called 'Project Management Planning Quality (PMPQ)'. The model consists of the two following components:

- project manager's know-how, including processes for which a project manager is responsible, derived from the PMBOK;
- organizational support offered by the performing organization.

The PMPQ model identifies 16 know-how processes and output and 17 organizational support processes and products. The processes were grouped into knowledge areas, based on the PMI classification

(in effect at the time) and on existing Project Management maturity model, 9 Knowledge areas (Project Management Institute, 2013) for Project Know-How and 4 Knowledge areas for Organizational support.

The model is structured to convert all these variables into an overall quality indicator. To achieve this purpose a relative importance, or weight, has been assigned to each process. Equal weight was assumed for the two groups, Know-How and Organizational, and also equal weight was assumed for each Knowledge Area. The weight of a specific process within a certain area depends on the number of processes in that area. The PMPQ index, that evaluates the quality of project planning process in the organization, is calculated as a weighted average of the 33 processes evaluation. But, indeed, the focus of the work is not on scheduling process and it is not construction-oriented.

The Practice Standard for Scheduling of the Project Management Institute (2007) describes the schedule development process good practices and components. Key points in the schedule development process are needed for scheduling quality: schedule components and data; schedule development process activity definition; schedule model characteristics; project control features. The Scheduling Maturity Model (Association for Project Management, 2012) has the aim of measuring an organization's ability in implementing and applying a scheduling process, with the aim of producing a good quality and robust schedule. The Schedule Maturity Model can be used for the assessment of a single project schedule or to benchmark the quality of the scheduling process through the organization, and it is based upon the definition of 28 attributes, classified into 7 requirements: process and toolset; structure and hierarchy; integration; resource/cost integration; risk; update and maintenance; and environment.

Quality of schedules

Quality of schedules entails requirements specification and performance metrics to define a quality schedule. Schedule quality assessment was the aim of the study of Russell and Udaipurwala (2000). Here, the perspective on schedule quality assessment is related to construction strategy, 'the plan of attack', plus the timing of activities. Russell identifies various indicators of schedule quality, grouped under several headings: accuracy and completeness, consistency with other planning documents, good practice/workability and benchmarks for control. Abstraction and compliance with contract documents are quoted but not examined in the cited literature.

AACE International (AACE) Recommended Practices (Douglas, 2006; Douglas and Gransberg, 2009)

include the 'Schedule Quality Analysis' and a guideline for schedule constructability. Schedule Quality Analysis means the checking of the schedule specification compliance, the verification of the schedule integrity (i.e. schedule mechanics and constructability) and the schedule validation. The guideline for schedule constructability, instead, entails a review process of a construction schedule, termed Schedule Constructability Review (SCR). The goal of SCR process is to assess whether the schedule is comprehensive and complete. Constructability can be defined as the use of construction knowledge and experience in planning, design, procurement and field operation to achieve overall project objectives (Douglas, 2009; Douglas and Gransberg, 2009).

The Practice Standard for Scheduling of the Project Management Institute (2007) defines a Conformance Index and a Conformance Index Assessment process to evaluate schedule quality. The GAO 'Schedule Assessment Guide' (2012) describes recommended best practices for project schedules. The guide focuses on project schedule quality to help managers and auditors ensure that the project schedule is reliable. The GAO guide provides 10 best practices associated with a high quality and reliable schedule.

The US Defence Contract Management Agency (DCMA) has defined a well-known 14-point metrics aimed at identifying potential problem areas with a contractor's Integrated Master Schedule (U.S. Defense Contract Management Agency, 2012). The DCMA 14-point schedule metrics is a tool that supports the schedule analysis to determine whether it is a realistic schedule or not, i.e. gives a metrics for assessing schedule quality. The schedule quality assessment can also be performed by an automated MS Project Macro developed by the agency.

The National Defence Industrial Association (NDIA), working group of Industrial Committee for Programme Management, published the 'Planning and Scheduling Excellence Guide (PASEG)' to provide the project management team, including new and experienced master planners/schedulers, with practical approaches for building, using and maintaining the project master schedules (2012). The guide encompasses 'Generally Accepted Scheduling Principles' (GASP), 10 quality control steps to validate the Integrated Master Schedule and a list of metrics that can be used to assess schedule health. The PASEG guide first introduces the term 'Schedule Health Assessment' as a quality control of project schedule and suggests the implementation of an automated Schedule Health Assessment tool. The PASEG approach of Schedule Health Assessment is different from the procedure proposed in the following paragraphs, as it focuses only on the 'mechanics' of the schedule, and it is not construction oriented. The same observation can apply also to the previously cited guides and metrics.

Moosavi (2012) and Moosavi and Moselhi (2012, 2014) defined a structured methodology to assist owners in the evaluation and approval of detailed schedule of contractors. In essence, it is a check list that covers a set of overall requirements for good schedules, concerning both development process and final schedule. The methodology has been implemented in an automated computer application called 'Schedule Assessment and Evaluation – SAE' developed to assist owners in the review of project schedules. The SAE performs schedule evaluation in three tiers:

- (1) Assessment of the schedule against industry recommended practices;
- (2) job logic assessment of construction trades;
- (3) assessment of construction productivity and of crew size considered for a number of commonly used trades in building construction.

The method is based on the evaluation of 48 criteria for Schedule Health Assessment including conceptual provision as well as quantitative requirements. The criteria are divided into three major categories: contractual compliance, schedule development and schedule components. In the first step of the research (Moosavi, 2012), the criteria were classified into conceptual provisions and quantitative provisions, actually they are classified into 8 obligatory criteria and 40 complementary criteria (Moosavi and Moselhi, 2014). The contractual management approach is believed to be a limit of the SAE method.

Research methods

The definition of the characteristics of a good quality schedule can be a challenging task. However, some experts from academia and professional institutions have proposed planning standards and schedule quality assessment methods. The seminal work of De La Garza (1990) and the consequent research and standardization efforts indicated the way forward for a construction schedule quality assessment. From this starting point, and passing through the definition of Project Management and Planning Maturity Model (Zwikel and Globerson, 2004), a research line has been developing from various and different roots, citing before all the works of Birrel (1980) and Laufer and Tucker (1987), which aim both at creating the conditions of producing a good construction schedule, thought as a symbolic tool of the planning effort of the project management team. The Schedule Management Maturity Model of Association for Project Management (2012) is a step forward in this direction. The main idea is not only to measure schedule adequacy, but also to indicate the processes, the phases and the working environment needed to create a robust schedule.

With this perspective, a method for construction quality assessment has been developed, with the aim of being also a guide for project schedulers in the scheduling process. Actually, almost all existing guidelines and standards about schedule quality are control oriented, and do not sufficiently highlight the schedule development phase. Moreover few consider the building and construction dimension of the production process and most of them have a strong legal accountability connotation.

First, it is thought that construction process and technology knowledge is of paramount importance in schedule management and development, and the proposed method highlights construction process requirements of project scheduling. This is seen to be a relevant contribution of the proposed Schedule Health Assessment approach. Then, another contribution is the aim at creating a guide for the project schedulers to be used in the design phase and for updating during project work execution.

The research methods followed are the constructive research approach (Lukka and Kasanen, 1995; Lukka, 2000) and this producing a proof of concept experiment for the feedback phase. Firstly, the relevant requirements needed for the development of an adequate construction schedule have been detected from the pertinent literature. Secondly, a thorough understanding of the applicable requirements was obtained by sample applications on project schedules. The solution idea proposed was to create a schedule management approach to qualify, guide and control the scheduling process. The approach can be used in both cases, the one of owner's consultant or the one of a project scheduler of a Construction company. As small companies are expected to have more resource problems (Hussain and Werne, 2005), the proposed method can be used as a facilitator of the scheduling process in the very common case of small – medium construction company projects. The constructed procedure was termed Schedule Health Assessment and it was developed with a simple set of score sheets to record the quality analysis performed. The evaluation of the quality level achieved by the construction schedule is performed through five KPIs, termed Schedule Health Indicators. Thus, the research is believed to produce an innovative 'construction' meant to solve the initial real-world problem of low quality level of construction schedules (Lukka, 2000). The developed method can also offer a conceptual framework of the scheduling problem for construction in general.

The research work develops in three steps (Figure 1). The first step is inductive and addresses the analysis of all the schedule quality requirements defined by researchers and by international standards or recommended practices. One hundred and fifty-six

specific schedule quality requirements have been evaluated and classified from pertinent literature.

The second step involves the selection of a group of 75 requirements divided into 5 classes of requirements. The selection process was performed identifying all pertinent requirements found in literature, and grouping them into classes of requirements. After this, the developed method performs the evaluation of the construction schedule quality thorough detailed requirements' check lists. A weighted approach allows to assess the global 'health' of the evaluated schedule.

In the third step, the Schedule Health Assessment proposed procedure is tested on a sample case study, concerning both the planning and the controlling

phase. The case study offers the possibility of proof of concept and generalized conclusions (Lukka and Kasanen, 1995), because of the possibility to discuss specific results and the subject area of construction scheduling in general.

Schedule Health Assessment: quality indicators

Main components of construction schedule quality

Many components are required in the development of a good quality project schedule, but two of them are believed to be more relevant to create a construction-oriented scheduling model, as described by literature. Construction schedule quality is, indeed, the result of the interaction between two main components, construction knowledge transferred into project schedule and schedule mechanics, the latter meaning the mathematical-related part of the schedule, mainly inherent to network logic and time computation. The assumption is that a standard construction schedule is basically prepared applying well-known networking methods like Precedence Diagramming Method, and using a software application such as MS Project or Primavera P6. By construction knowledge, it is meant the set of information related to construction technology implementation in the building construction process, while by schedule mechanics knowledge it is meant the set of information related to scheduling technology, i.e. scheduling and activity network rules. Actually construction knowledge implementation refers to the constructability concept, as previously addressed, i.e. a system for achieving optimum integration of construction knowledge and experience in planning, engineering, procurement and field operations in the building process, and balancing the various project and environmental constraints to achieve overall objectives (Institution of Professional Engineers New Zealand, 2008). Actually constructability concept can be useful for quality assessment to review construction processes from start to finish during pre-construction phase. The aim of constructability check is to identify obstacles before the project is actually built to reduce or prevent errors, delays and cost overruns.

Instead schedule mechanics knowledge refers to the project management methods and techniques to plan and schedule a project. As most of construction projects are scheduled with a networking technique, e.g. Precedence Diagramming Method, implemented with a computer software, schedule mechanics is the set of rules that allows the performance of the scheduling process with a critical path method on a computerized application. While in most standards, recommended practices

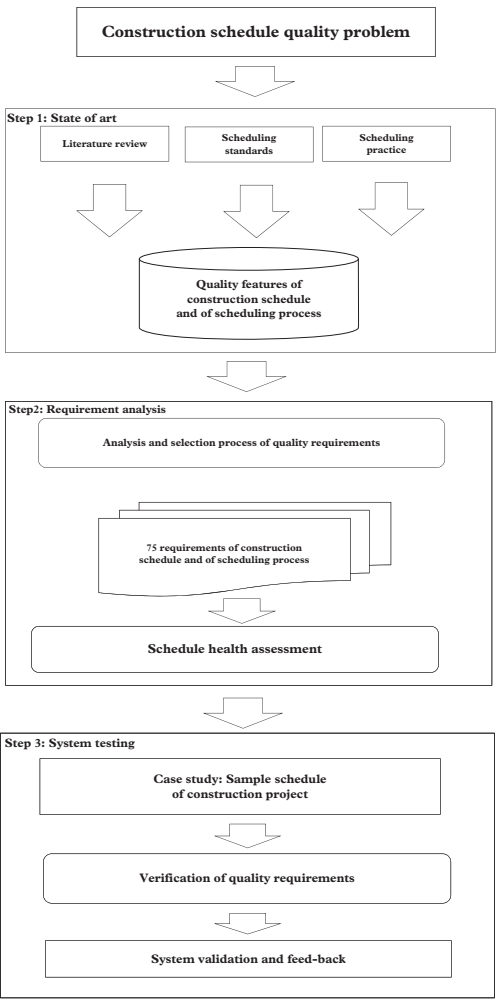


Figure 1 Research procedure

and pertinent literature construction knowledge and schedule mechanics knowledge are addressed with separate approaches, it is believed that an integrated approach could be more effective for a construction schedule. Two specific quality indicators of the proposed method are dedicated to the assessment of these two areas of knowledge. Construction knowledge assessment mostly depends on activity definition and on structure of network logic. These and other important requirements can be found in the Indicator no. 2 (Table A2). Schedule mechanics knowledge mostly depends on network logic structure and critical path time analysis, as described by the Indicator no. 3 (Table A3). The proposed schedule quality assessment procedure has been termed as Schedule Health Assessment, as suggested by the PASEG guide in 2012 (Program Management System Committee, 2012), because it is felt that this denomination quickly brings to the reader the concept of good quality, good health indeed, of the schedule as a part of the project management process. But it is also felt that the PASEG guide is too much a generic guide as a starting point for construction schedule evaluation process, because it is not construction oriented and focuses mostly on schedule mechanics (and activity definition and network structure). The most important quality indicators, or health indicators, should be related to construction knowledge and schedule mechanics knowledge, but this is not enough. Quality indicators should also describe all the components of schedule quality, and must concern with scheduling process itself, with cost and resource data, and with the control process performance. So the developed quality assessment procedure is based on the identification of five quality indicators or KPIs, and on the measure of their values. Each schedule indicator aims at defining a quality level of schedule performance concerning a specific component, thus contributing to assess overall schedule health.

Health Assessment Indicators

The structure of the proposed method is based upon five Health Assessment Indicators of schedule quality. These indicators have the task of measuring the performance of the scheduling process and of the produced schedules. Each indicator is composed of different classes of requirements, simply termed requirements which in turn are made up of detailed requirements, being the 'measurement items' of the method. The method originates from a literature analysis in which 156 different detailed quality requirements for scheduling have been detected. These detailed requirements have been used as background data, they have been

classified, analysed and grouped depending on their specific subject, content and purpose. The classification of these requirements was performed in three steps. In the first step, all the found literature requirements have been listed and understood. In the second step, the literature requirements have been classified using candidate categories for the targeted schedule quality assessment system. This resulted in the five Schedule Health Indicators, which were further divided into classes of requirements. In the third step, the selection process has been finalized with the following criteria: unicity of the specification (i.e. avoiding repetitions); level of importance related to the aim of the research; usefulness in the construction sector. The requirement list has been improved by adding a construction safety detailed requirement. This process produced 75 detailed requirements, which are classified into 5 groups to constitute the five different Schedule Health Indicators.

The identified five *Schedule Health Indicators* are the following (Figure 2):

- (1) General requirements;
- (2) construction process requirements;
- (3) schedule mechanics requirements;
- (4) cost and resources requirements;
- (5) control process requirements.

The objectives and aims of each *Schedule Health Indicator* are the following:

- Indicator no. 1 'General requirements' consists of a set of provisions that are aimed at conforming the schedule production process to quality standards related to the developing phase, to the schedule as a product and to the contract provisions for the construction project (Appendix 1: Table A1).
- Indicator no. 2 'Construction process requirements' consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the execution phase of the construction project. The objective is the construction process safety and optimization (Appendix 1: Table A2).
- Indicator no. 3 'Schedule mechanics requirements' consists of a set of provisions that are aimed at conforming the schedule to quality standards related to the planning/monitoring phase of the construction project with the critical path method (Appendix 1: Table A3).
- Indicator no. 4 'Cost and resources requirements' consists of a set of provisions that are aimed at verifying that the activities of the project, and the project itself, can be executed within the calculated time and budget, due to resource and cost loading to activities (Appendix 1: Table A4).

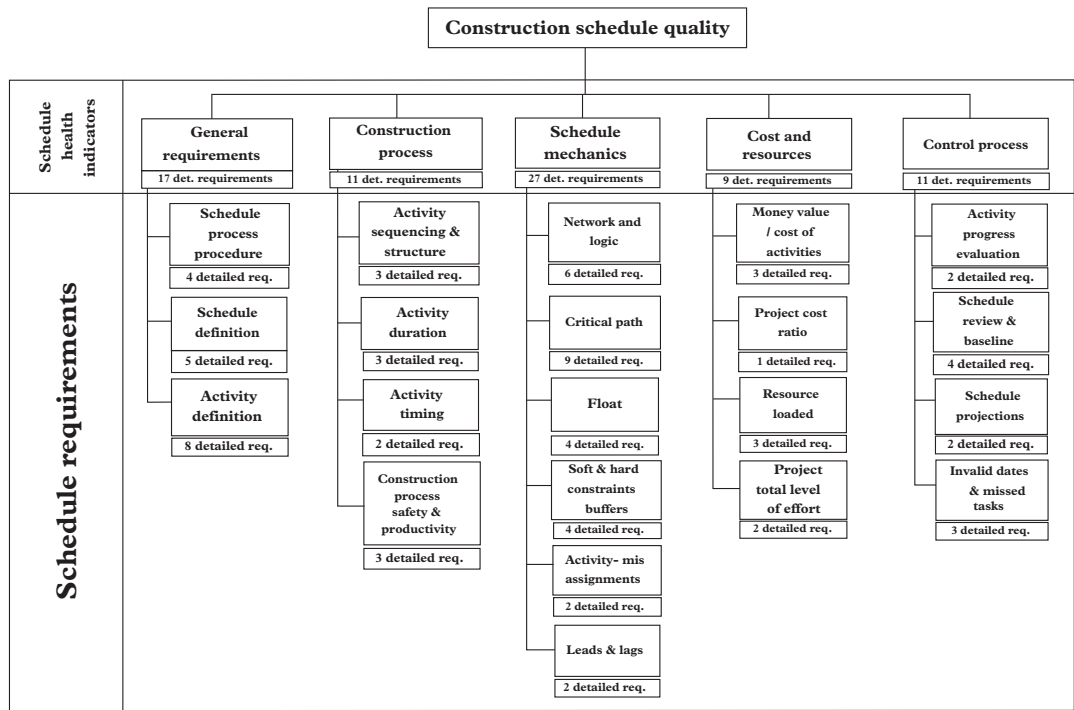


Figure 2 Schedule Health Indicators and schedule requirements

Indicator no. 5 ‘Control process requirements’ consists of a set of provisions that are aimed at allowing an efficient project control process through schedule updating and replanning processes (Appendix 1: Table A5).

Each indicator is, in turn, composed of a number of requirements aimed at the quality assessment of the produced schedule, and at developing a construction project schedule conforming to the suggested method.

The information content of each indicator is first expressed by ‘Requirements’, than each of them is composed of more specific ‘Detailed Requirements’, which, in turn (and if needed) are composed of ‘Requirement Specifications’. The method classifies 21 requirements, 75 detailed requirements and 54 requirement specifications (Bragadin and Kähkönen, 2014).

The schedule quality measurement process is organized through a Breakdown Structure (Figure 2). First detailed requirements with optional requirement specifications are checked. The satisfaction of detailed requirements gives a measure of each Schedule Health Indicator satisfaction. Then each indicator is weighted

and a measure of total schedule quality can be found. A brief description of each Schedule Quality Indicator and its component requirements is following. The complete list of detailed requirements is included in the appendix to the text (Tables A1, A2, A3, A4 and A5).

The General Requirements Indicator

The General Requirements Indicator (Figure 2) is composed of three requirements: Schedule Process Procedure; Schedule Definition; and Activity definition. The Schedule Process Procedure requirement aims at conforming the schedule development process to four related quality standards, namely detailed requirements; definition of an activity coding structure; identification of project calendars; involvement of main subcontractors and following of a standardized scheduling procedure. The Schedule Definition requirement entails five more detailed requirements about schedule structure and contract compliance. In particular, it concerns schedule logic vertical and horizontal integration, meaning that detailed tasks must flow-up to summary tasks and there must be logical

relationships and time-phasing between tasks. The Activity Definition requirement encompasses detailed requirements mainly about the total number of activities, activity name and definition, WBS and responsibility assignment (Appendix 1: Table A1).

The Construction Process Requirements Indicator

The Construction Process Requirements Indicator is composed of four requirements: Activity Sequencing and Structure adequacy; Activity Duration, Activity Timing and Construction Process Safety and Productivity (Figure 2). They are mainly concerned with schedule constructability, meaning the proper sequence of construction phases and the optimization and safety of the construction process modelled by schedule. Activity Sequencing aims at defining a construction-oriented network logic, while Activity Duration is related to the duration estimate and the continuity of production during activity execution. Activity Timing detailed requirements are mainly related to proper scheduling of weather-sensitive activities. Construction Process Safety and Productivity is related to work efficiency of the construction site, and entails detailed requirements about work continuity, work flow of resources, work space and safe work areas (Appendix 1: Table A2).

The Schedule Mechanics Requirements Indicator

Schedule Mechanics Requirements Indicator aims at conforming the network schedule structure to critical path method related detailed requirements (Figure 2). So the indicator is composed of detailed requirements related to network and logic, critical path and critical activities, float dimensions and computation, soft and hard constraints, buffers, leads and lags, activity misassignments (Appendix 1: Table A3). Schedule mechanics requirements are believed to have an high impact on schedule quality. Network and logic requirement aims at conforming the PDM network structure to requested features in terms of absence of open-ended activities, proper use of summary task logic, no activity with missing predecessor or successor, a correct number of relationship between activities, frequent use of finish-to-start relationship types and few activities with an high duration. Critical path detailed requirements are bound to properly define critical path logic and critical activities of the network, and also entail few quantitative indicators as the Critical Path Length Index (CPLI), Schedule Criticality Rate and Near Criticality Rate, as proposed by the DICMA 14-point standard. Float requirements are related to float computation

and dimension. Excessive total float and negative total float are discouraged. Soft and Hard Constraints and Buffer detailed requirement entail ASAP and ALAP computation, the type and number of constraints and the presence of buffers. As defined by Activity Misassignment and Empty Event detailed requirements, no such activity or event must be found in the network. Lead and Lags provide a small amount of relationships with lead times, and no relationships with negative lead, termed lag.

The Cost and Resources Requirements Indicator

Cost and Resources requirements indicate the feasibility of the construction schedule as they implicate the effective amount of economic and working resources (Figure 2). The indicator is composed of four requirements: Monetary Value/Cost of activities, Project Cost Ratio, Resource-Loaded Activities and Project Total Level of Effort (Appendix 1: Table A4). The Monetary Value/Cost requirement entails the monetary load of activities in terms of cost or prices of all the activities, the total monetary value of the project and the optimized distribution of progress payments, including the Project Cost Ratio Index. The Resource-Loaded Activities requirement detects the resource loading of activities, the planned productivity which has contributed to the duration computation and the possibility of resources conflicts. Project Total Level of Effort and Project Effort Ratio can be important markers of the schedule feasibility.

The Control Process Requirements Indicator

Control Process requirements have the task of facilitating Project Control activities. The four requirements defined are the following: Activity Progress Evaluation, Schedule Review and Baseline, Schedule Projections and Invalid Dates and Missed Tasks (Figure 2 and Appendix 1: Table A5). Activity Progress Evaluation is composed of two detailed requirements: the percentage complete of activities and schedule slippage. The Schedule Review and Baseline requirement has the aim of evaluating the schedule maintenance process, and entails actual progress definition, the report of variances and the Baseline Execution Index (BEI), the latter being of major importance for the evaluation of the actual progress of work related to schedule forecast (U.S. Defense Contract Management Agency, 2012). Schedule Projections requirement entails two detailed requirements: schedule projections and corrective actions. These two items aim at revealing the implementation of schedule updating and control actions. Control process requirements list ends with the invalid

dates, missed tasks and out of sequence detailed requirement, which all are well-known indicators of the accuracy of schedule updating.

Schedule Health Assessment

Schedule Health Assessment proposed method

Schedule Health Assessment is a method to perform the quality assessment of a construction schedule. The aim is to ensure the quality of the construction schedule starting from its design and development phase, through the maintenance phase during project work execution until project completion. Beyond the intended use for quality control purposes, the developed Schedule Health Assessment procedure also aims to assist project team and project schedulers to prepare a good quality schedule which fits the needs of project owner, contractors and stakeholders. It is, indeed, a procedure that checks the quality of the construction schedule which can be used by the contractor in the development and maintenance of the project schedule or by the owner in the evaluation and review of the schedule submitted by the contractor.

The Schedule Health Assessment proposed method also produces a report containing a set of data or statistics reviewed for compliance up to a set of 75 requirements belonging to five schedule KPIs termed Schedule Health Indicators. Schedule Health Metrics are different from schedule execution metrics, as they focus on schedule adequacy, while schedule execution metrics focus on the performance of project work processes (Program Management System Committee, 2012). For instance, in the Schedule Health Assessment procedure it is evaluated if a BEI has been computed, and not if it has a favourable or unfavourable value or, generally speaking, if the project execution is running in line with forecasted performance or not.

The construction schedule quality model

The Schedule Health Assessment proposed method uses 75 detailed requirements to constitute a metrics to measure schedule compliance to a quality model of the process/product 'construction schedule'. The quality model was built through study and analysis of pertinent literature and standards, and from suggestions from practical experiences. Each detailed requirement constitutes an item of construction schedule quality that can be a quality-related subprocess, i.e. 'Main sub-contractors participation', or a quality-related component, a schedule feature or an item, i.e. 'Critical path & critical activities', 'Relationship ratio' or 'Monetary Value of Activities'.

Thus it is quite simple to evaluate if the quality-related subprocess has been performed by project team or if the quality-related component was included in the schedule. The evaluation is done by a checklist score-sheet where one point is earned if the detailed requirement check is positive (pass) or no points are assigned if the check is negative (fail). A similar evaluation process is proposed by the PMI for the Schedule Conformance Index (Project Management Institute, 2007). Concerning the evaluation of each single detailed requirement, if needed more specific 'requirement specification' has been used to facilitate the evaluation process. 'Requirement specification' list has not been included for brevity sake. Detailed requirements are grouped into five Schedule Health Indicators, and a Requirement Breakdown Structure (RBS) has been encoded to guide and facilitate the assessment process. An excerpt of the scoresheet used for the evaluation of quality of the sample case study schedule can be found in Figure 3.

Thus, a quality assessment of the construction schedule can be performed with a rather simple and quick method. But for evaluation purposes the procedure needs to take into account the relative importance of each set of requirements to the global quality of the schedule. Indeed, the five Schedule Health Indicators do not have the same importance in planning and scheduling process. While some of the studies and recommended practices focus on the requirements related to constructability (De la Garza, 1990; Dzeg and Lee, 2000, 2004; Dzeg and Tommelein, 2004; Douglas and Gransberg, 2009), which mainly correspond to the Schedule Health Indicator no. 2 (Construction process requirements), most of guidelines and standards, (Project Management Institute, 2007; Program Management System Committee, 2012; U.S. DICMA, 2012) highlight the importance of the scheduling process and product quality only addressing schedule development and mechanics, which correspond to Schedule Health Indicator no. 1 and no. 3, (General requirements and Schedule mechanics requirements). Also Moosavi and Moselhi (2012) who performed a survey based on feedback from professionals of the construction industry, indicate as top schedule assessment criteria the ones related to the scheduling process and to schedule mechanics. Although the cost and resource loading requirements are believed to be fundamental components of the planning, scheduling and controlling processes, they seem to have less value for schedule quality assessment as described in pertinent literature. The same can be said for the project control requirements. Assuming that all the relevant requirements for quality evaluation of a construction schedule have been identified, there is a need to assign them a relative importance, a weight, to structure a quality assessment method (Paquin *et al.*, 2000).

Schedule health indicator Requirements	RBS	#	Detailed requirements (Specific requirements)	Total Score	Score Notes
3. Schedule mechanics requirements:	3			6	
a. Network and logic	3.a			6	
	3.a.01	29	Open ended activities (activities without affiliation) should be avoided	1	0 or 1
	3.a.02	30	Summary tasks with logic relationships should be avoided	1	0 or 1
	3.a.03	31	Missing logic: there should not be any incomplete tasks with missing logic	1	0 or 1
	3.a.04	32	Relationships ratio: total number of relationships/total number of activities should be limited	1	0 or 1
	3.a.05	33	Relationship types (FS, SS, FF, SF). Start to Finish SF is counter-intuitive, it should be avoided	1	0 or 1
	3.a.06	34	High duration: the number of incomplete tasks with high duration should be limited	1	0 or 1

Figure 3 Sample checklist of the Schedule Health Assessment proposed method

Since there is no prior information concerning the relative importance of each detailed requirement belonging to each Schedule Health Assessment Indicator, they are assumed to have the same importance in their own group. But the number of detailed requirements of each Indicator seems to be in direct relationship to the level of relative importance of the Indicator related to the others, so the developed method weights each Schedule Health Assessment Indicator in function of the number of the composing detailed requirements. A similar logic was implemented to structure the weights of the model of Zwikael and Globerson (2004).

Health Assessment procedure

The method identifies a number of measurable detailed requirements for each Schedule Health Indicator of the construction project schedule. Then quality evaluation of the schedule can be performed with a check list (Figure 3) of detailed requirements satisfaction. With this information the quality level indicated by each Indicator can be assessed and a comprehensive quality level, the Schedule Health Assessment, can be evaluated through a weighting process. The procedure and results of the proposed method are shown in Figure 4, where a schedule performance chart is presented to show the results of the proposed procedure.

The overall Schedule Health (SH) can be quantified with a percentage grade. For each Schedule Health Indicator (S_i), the weight (W_{gi}) indicates the relative importance of each indicator to the others being used to measure the overall performance of the schedule of the construction project.

$$SH = \sum_{i=1}^5 S_i \times W_{gi} \quad (1)$$

where SH = overall Schedule Health Assessment of the construction project; S_i = Schedule Health Assessment

Indicator (i); W_{gi} = weight of Schedule Health Indicator (i), compared to other indicators of the schedule. The weight can vary related to the number of Indicators used for the evaluation. To highlight this process, a specifying character can be added: W_{gmi} = relative weight for master schedule evaluation; W_{gdi} = relative weight for detailed schedule evaluation; W_{gci} = relative weight for maintenance schedule evaluation (Figure 5).

The model of Equation (1) allows to measure and quantify the overall health of the construction project schedule.

The Schedule Health Assessment Indicator (S_i) for the requirement group (i) of the scheduling process is evaluated with the percentage of adherence to detailed requirements and specifications for schedule quality. The indicator is calculated with the following Equation (2):

$$S_i = \frac{\sum_{j=1}^s DR_{ij}}{\sum_{j=1}^s R_{ij}} \quad (2)$$

where S_i = Schedule Health Assessment Indicator (i); DR_{ij} = estimated detailed requirements met by schedule (j) for the Schedule Health Assessment Indicator (i); R_{ij} = detailed requirements (j) for the Schedule Health Assessment Indicator (i); s = total number of detailed requirement of the Indicator. Note that for each detailed requirement satisfaction the DR_{ij} value is 1, if the schedule does not meet the requirement the DR_{ij} value is zero.

A pro-active method for construction schedule development

The Schedule Health Assessment proposed method has also the goal of supporting project planners in the development of a high-quality project schedule. With

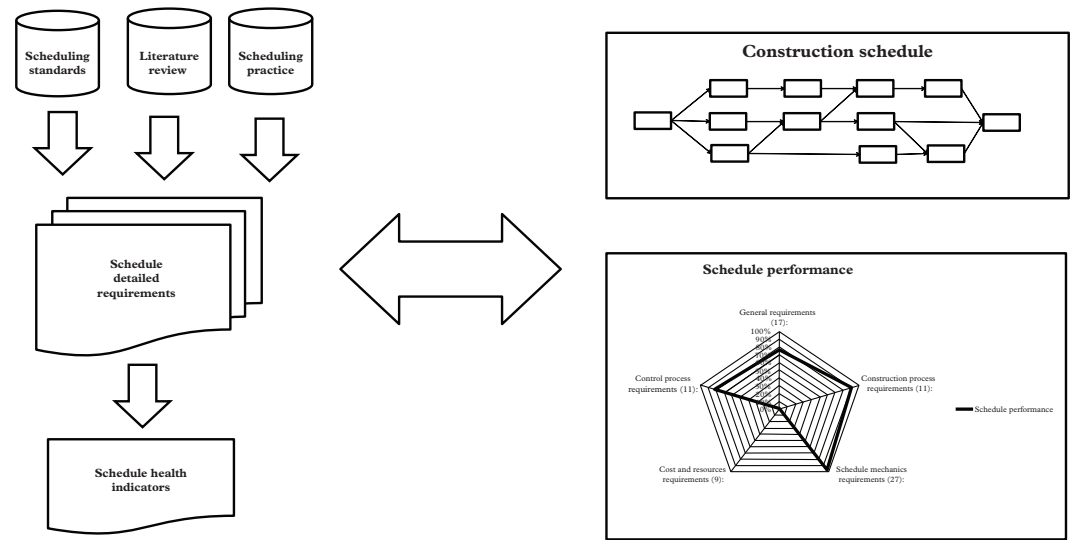


Figure 4 Proposed method framework: schedule requirements vs. schedule performance

Schedule health indicators:			General	Construction process	Schedule mechanics	Cost and resource	Control process
Schedule development phases	Planning phase	Step one: master schedule	31%	20%	49%	/	/
		Step two: detailed schedule	27%	17%	42%	14%	/
	Control phase	Step three: maintenance	23%	15%	36%	12%	14%

Figure 5 Schedule development phases and related health indicators relative weights

this goal in mind, Schedule Health Indicators have been put in a sequence thinking at their progressive implementation during the planning, scheduling and controlling process. The construction schedule development process can be implemented with three steps: master schedule, detailed schedule and schedule maintenance. The first and the second step form the planning phase, while the third step is the control phase.

- (a) Master Schedule. In the first step, project schedulers can start schedule design and development following the general requirements. Then Master Schedule can be created following construction

- process requirements and schedule mechanics requirements. Once project schedule is developed, checklist scoresheets can be used to assess schedule health level through Indicators number one, two and three. This control step provides a feedback that can be used to improve schedule quality.
- (b) Detailed Schedule. In the second step, cost and resources can be added to the construction schedule following cost and resources requirements. This process generally involves a more detailed definition of project activities. Then a

control feedback can be performed mainly through quality evaluation of Indicator number four, but also indicators number one, two and three are considered again.

- (c) **Schedule Maintenance.** When project execution phase commences, the control process of project execution can start and the updating and maintenance processes of schedule can follow the control process requirements' track. Mainly the quality evaluation is performed with the checklist scoresheet of Schedule Health Indicator number five. This can give a useful control feedback to project managers and schedulers, highlighting schedule updating items to improve. In the schedule maintenance phase, indeed, replanning and rescheduling are performed and all of the five indicators are needed.

The proposed three steps for construction schedule development and quality checking allow project scheduler to perform the proposed Schedule Health Assessment method related to the needed level of schedule application. Weights of indicators vary depending on the level of implementation. In fact for real-life construction projects a partial schedule development is very common, i.e. only phase one, or one and three can be fully implemented (Figure 5).

The proposed procedure can be easily performed by the project scheduler during each scheduling phase analysing schedule features, reviewing the file(s) produced by the scheduling software and completing the proposed checklists. It is possible to modify weights from project to project based on project priority. As the proposed method basically consists of five checklists (one for each indicator), it is believed that completing the checklist is an easy task for the project scheduler. The procedure was tested on the sample project schedule following, but has been already tested on other schedules in previous papers (Bragadin and Kahkonen, 2014, 2015).

Schedule Health Assessment implementation and sample testing

The developed Schedule Health Assessment method has the goal of being simple and easy to be applied by practitioners. So the evaluation process can be performed easily by the project scheduler assessing schedule performance as measured by the requirements specified in the checklists. Note that the requirement lists can be emended to fit to specific project needs. The Schedule Health Assessment procedure can be accomplished in a straightforward manner. First the detailed requirement check list is evaluated. Each Schedule Health Indicator (e.g. General requirement)

is composed of requirements (e.g. Schedule Process Procedure, Schedule Definition and Activity Definition). Each requirement is made up of various detailed requirements, as previously defined. The scheduler checks if each detailed requirement is satisfied by the project schedule. For each detailed requirement satisfied by the project schedule a point is earned. Then with Equation (2) the value of each Schedule Indicator is found. The weighted sum of each indicator is the Schedule Health (SH) assessment ranking (Equation 1).

If the Schedule Health Assessment is performed prior to project execution for a master schedule, the set of weights related to Indicators one, two and three (W_{gm}) will be used. In case of evaluation of a detailed schedule the Indicator number 4 will be included and the related set (W_{gd}) will apply. If the Schedule Health Assessment is performed in the schedule maintenance phase all Indicators are needed and the related set of weights (W_{gc}) will apply (Figure 5).

Testing of the proposed method has been carried out in a sample case study covering both the detailed planning and the controlling phases. A simple detailed schedule of a construction project of a shopping centre has been tested. The construction schedule was developed with MS Project. The network is composed of 148 activities and a *fragnet* of the sample schedule can be found in Figure 6. A *fragnet* is a network fragment, or a portion of the project schedule that relates to a specific project phase. First the construction detailed schedule was evaluated, and the encompassed Indicators were 'General Requirements', 'Construction Process', 'Schedule Mechanics' and 'Cost and Resources'. Thus the W_{gd} set of weights was used. Then the Health Assessment was performed for the control phase and schedule maintenance, thus involving all of five indicators and the use of the W_{gc} set of weights (Figure 5).

In the planning phase the applied weights (W_{gdi}) for the detailed schedule are computed on a set of only 64 requirements. Applying Equations (1) and (2) the final grade SH achieved by the schedule was found. The SH value was 67%. The Table 1 shows the report scoresheet of the Schedule Health Assessment procedure for the sample project and Figure 7 summarizes the results with a performance graph.

The result obtained by the schedule was good enough for project management purposes, but suffered from a set of deficiencies. The 'General Requirements' indicator earned 13 positive points out of 17, thus showing a very good schedule and activity definition process though revealing the absence of a standardized schedule process procedure. Also the 'Construction Process Requirements' indicator obtained a good score of 10 points out of 11. In fact almost all the detailed

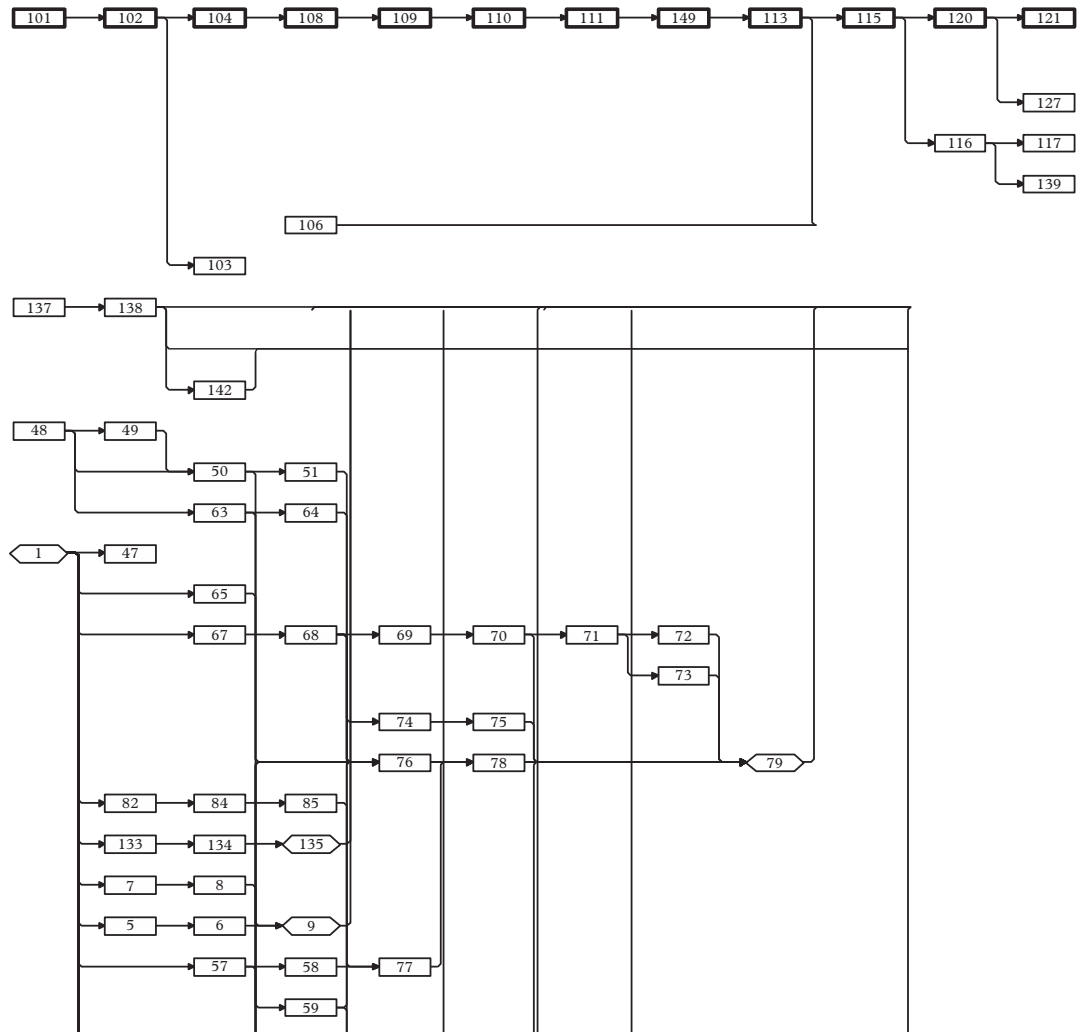


Figure 6 Snapshot of a network fragment of the sample schedule, planning phase – detailed schedule (performed with MS Project)

requirements about activity sequencing, activity duration, activity timing and construction process safety and productivity were properly implemented. The schedule health Indicator no. 3, ‘Schedule Mechanics Requirements’ achieved a good grade, 19 points out of 27. Schedule requirements about computerized networking technique implementation were not completely satisfied by sample schedule. Network logic was clear and correctly implemented, but dangling activities were found. Critical path and float definition

were properly defined and no activity misassignments were found. Instead a number of negative lags (leads) and constraints were detected. No monetary value and few resources have been loaded, so only one point was earned by the schedule for the ‘Cost and Resources Requirements’ indicator, because of the satisfaction of the detailed requirement about resource conflicts analysis.

Above all, most of the schedule quality requirements of the planning phase were considered fulfilled

Table 1 Schedule Health Assessment: sample schedule report sheet – planning phase

No. Req.	Requirement description	Req. score	Indicator score	Wgd (%)	Si (%)	Swi (%)
(1)	General requirements (17)		13	27	76	21
(a)	Schedule process procedure (4)	1				
(b)	Schedule definition (5)	5				
(c)	Activity definition (8)	7				
(2)	Construction process requirements (11)		10	17	91	15
(a)	Activity sequencing & structure (3)	2				
(b)	Activity duration (3)	3				
(c)	Activity timing (2)	2				
(d)	Construction process safety & productivity (3)	3				
(3)	Schedule mechanics requirements (27)		19	42	70	30
(a)	Network and logic (6);	3				
(b)	Critical path (9)	9				
(c)	Float (4)	3				
(d)	Soft & hard Constraints, buffers (4)	1				
(e)	Activity mis-assignments (2)	2				
(f)	Lag & lead (negative lag) (2)	1				
(4)	Cost and resources requirements (9)		1	14	11	2
(a)	Monetary value/cost of activities (3)	0				
(b)	Project cost ratio (1)	0				
(c)	Resource-loaded activities (3)	1				
(d)	Project total level of effort (2)	0				

SH = 67

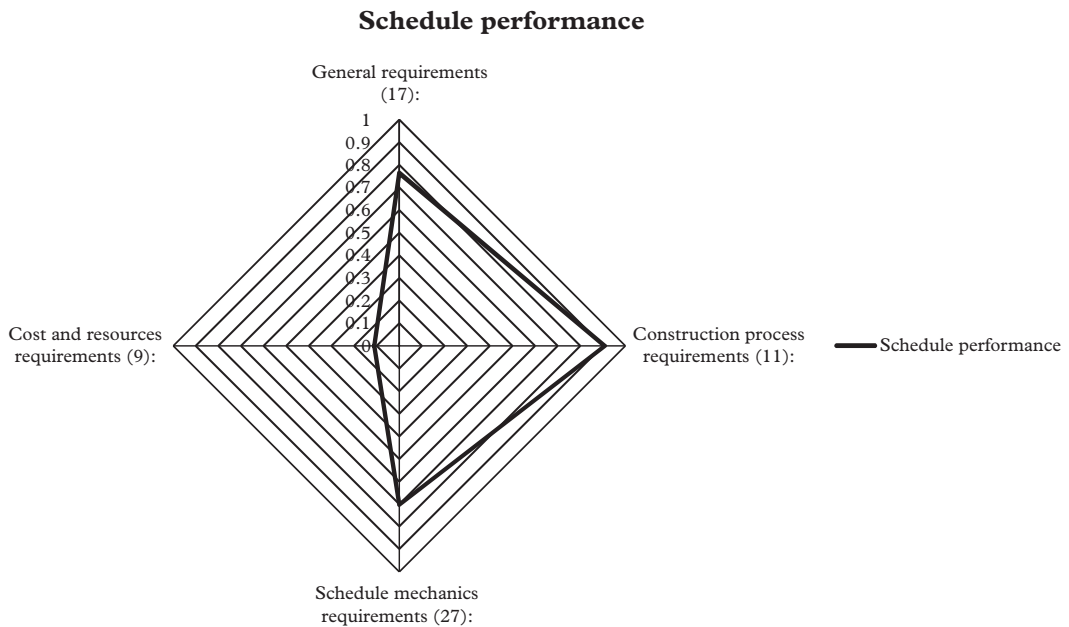
**Figure 7** Schedule performance graph of the sample detailed schedule

Table 2 Schedule Health Assessment: sample schedule report sheet – controlling phase

No. Req.	Requirement description	Req. score	Indicator score	Wgc (%)	Si (%)	Swi (%)
(1)	General requirements (17)		13	23	76	18
(a)	Schedule process procedure (4)	1				
(b)	Schedule definition (5)	5				
(c)	Activity definition (8)	7				
(2)	Construction process requirements (11)		10	15	91	14
(a)	Activity sequencing & structure (3)	2				
(b)	Activity duration (3)	3				
(c)	Activity timing (2)	2				
(d)	Construction process safety and productivity (3)	3				
(3)	Schedule mechanics requirements (27)		19	36	70	25
(a)	Network and logic (6)	3				
(b)	Critical path (9)	9				
(c)	Float (4)	3				
(d)	Soft & hard Constraints, buffers (4)	1				
(e)	Activity misassignments (2)	2				
(f)	Lag & lead (negative lag) (2)	1				
(4)	Cost and resources requirements (9)		1	12	11	1
(a)	Monetary value/cost of activities (3)	0				
(b)	Project cost ratio (1)	0				
(c)	Resource loaded activities (3)	1				
(d)	Project total level of effort (2)	0				
(5)	Control process requirements (11)		8	14	73	10
(a)	Activity progress evaluation (2)	1				
(b)	Schedule review and baseline (4)	4				
(c)	Schedule projections (2)	1				
(d)	Invalid dates and missed tasks (3)	2				
SH = 68						

by the sample schedule, as shown in the graph of Figure 7.

In the controlling phase the Schedule Health Assessment procedure was developed with the complete check list of the 75 requirements for schedule maintenance. The ‘Control Process Requirements’ indicator earned 8 points out of 11. Most of the schedule quality requirements were considered fulfilled by the sample schedule, and no invalid dates and missed tasks were found. Applying Equations (1) and (2) the final grade SH achieved by the schedule was found. The SH value was 68%. The Table 2 shows the report scoresheet of the Schedule Health Assessment developed method for the sample project, and the graph of Figure 8 presents Schedule Health Assessment results. A snapshot of the control barchart view of the sample schedule is shown in Figure 9.

Discussion

The Schedule Health Assessment procedure has been developed for completing the quality assessment of a construction schedule. A project schedule has a crucial importance as for project management and thus these

planning outputs are to be properly developed and maintained. Poor implementation of schedule in the construction sector is very common, especially in medium – small size projects. More than this, shortage and limits of network-based programming techniques for construction projects are very well known (Kenley and Seppanen, 2010). Thus improved understanding over the quality of construction project time management processes and relating solutions is seen to be an important component of project management research. A major finding based on the development of Schedule Health Assessment procedure is the identified need to guide the scheduling process, which is needed (i) to show the path for schedule preparation and (ii) to produce an effective approach for the project time management i.e. schedule implementation and control. The developed Schedule Health Assessment method has the aim of supporting project schedulers in the project planning phase to develop master and detailed schedules, and in the project execution phase, to support the schedule controlling process.

In the planning phase the project team needs to develop a sound and good quality schedule, and the planning process can be supported by following the Schedule Health requirements, first used as guidelines

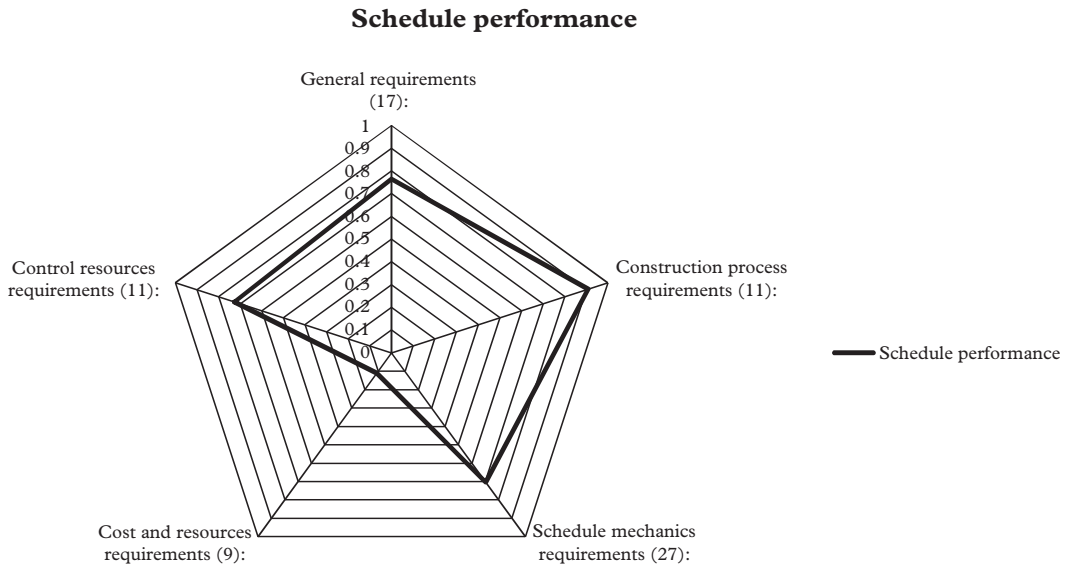


Figure 8 Schedule performance graph of the sample project, controlling phase, maintenance schedule

of the project management schedule subprocesses, and then used for quality control purposes at the end of the scheduling process to detect any weakness in the master or detailed schedule thus allowing the project scheduler and/or the entire project team to provide a remedy or to correct the schedule. Similarly, in the controlling phase the Schedule Health Assessment method can provide correct information for schedule maintenance.

It was found that the previous studies over construction-related scheduling focus mainly on contractual requirements, i.e. have a legal concern on duties and responsibilities of the parties in question, usually owner and contractor. The proposed method, instead, has the purpose of being a driver of the scheduling process, or in other words it can be understood as a schedule management-oriented solution. Beside this, there are many other differences between the proposed method and existing ones: the different number of requirements, the grouping and weighting system, the automatization vs. handmade checklist compilation. Also, the proposed method entails explicitly safety in the construction process requirements, and can be used in each stage of the development of the project schedule (master, detailed and maintenance).

Concerning the different phases of the construction process and their needs, the method was developed for two main purposes, at the contractor's detailed schedule level for the project execution and at the project manager's level once the contractor's schedule has been

uploaded and integrated into a master schedule. The weighting system of schedule indicators changes related to the level of application. It is also possible to modify weights from project to project based on project priority. The definition of such project-oriented weights will be object of future research.

The Schedule Health Assessment proposed procedure was also developed with the purpose of being a simple method, easy to be performed by construction Small and Medium-sized Enterprises (SME), which need a good quality level schedule but usually have scarce resources for this task. A non-structured interview with the company's project scheduler of the sample project revealed a substantial agreement on the results of the proposed method. In fact, the final grade of both Health Assessment procedures was almost 70%, which means a satisfactory/good level of the schedule. The little time amount available for project scheduling process was the main cause of the fair level of performance obtained. But the quality level was in line with the company's existing project practices and was also meeting contract provisions. Metrics for quality of a project schedule should also indicate a threshold of suitability for practical applications, i.e. if the schedule quality level fits for the purpose. Threshold values could change in function of project goals and characteristics. Limit values should be set case by case, cautiously. Future research should also be oriented to schedule metrics settings, always with the

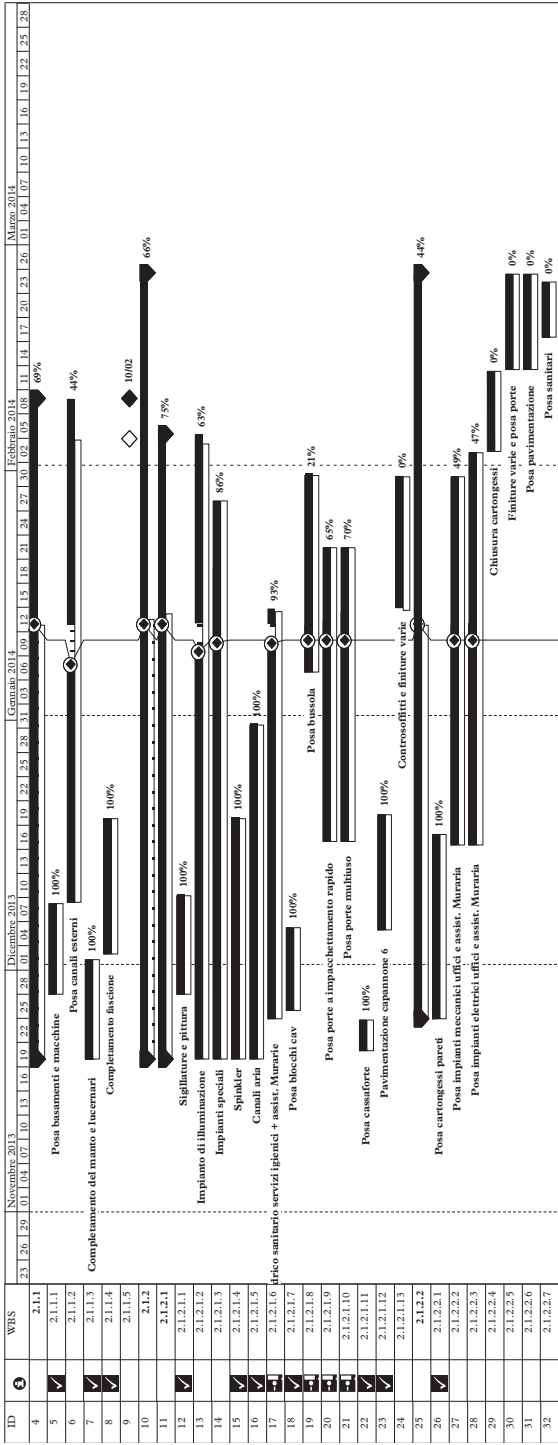


Figure 9 Snapshot from analysed sample schedule, controlling phase (MS Project)

aim of defining construction schedule quality guidelines to apply mostly in the scheduling developing process rather than in a schedule evaluation phase.

Conclusions

A Schedule Health Assessment method has been proposed with the aim of improving the quality of a construction schedule and scheduling process. The quality level of scheduling process and of schedule itself can be measured through five KPIs, termed Health Indicators, which are the following: general requirements, construction process requirements, schedule mechanics requirements, cost and resources requirements and control process requirements. The different classes of requirements can be used to measure schedule health related to the different phases of construction project: master schedule, detailed schedule and schedule maintenance. The Schedule Health Assessment method introduces checklists of detailed requirements which can be used as a guide to scheduling process itself. In fact, the method has also the aim of being a pro-active method for master and detailed construction scheduling i.e. it can be used as a guide in the schedule development process by project planners or for quality assessment for controlling purposes by project supervisors. It is believed that the proposed method has also the effect of increasing project control in the execution phase, as quality audit of the schedule maintenance process can have the effect of enhancing the monitoring and controlling process.

The proposed five Schedule Health Indicators are based on the 75 detailed requirements identified from pertinent literature and existing standards. A model and relative weights of the Indicators has been developed, and the weighted sum of the performance level of each indicator has been indicated to be the Health Assessment of the evaluated schedule. It is believed that a main result has been the description of the detailed requirements for each Schedule Health Indicator listed in the appendix (Tables A1, A2, A3, A4 and A5), which is seen as main new knowledge contribution. Future research has been planned to address indicators' weight for the evaluation process.

The proposed method was tested on a sample project, providing schedule performance charts for the detailed schedule and for the maintenance schedule process. The result of the Schedule Health Assessment procedure indicated an average quality level of the sample schedule. This means that further improvement of the evaluated schedule was possible, as to increase its schedule health level, but an interview with the company's project scheduler revealed that the evaluated schedule was believed to have the needed quality level.

This reveals much insight of real objectives into construction project scheduling, as it is believed that another step forward is still needed by project scheduling to become an effective production plan and not only a schedule.

As Schedule Health Assessment is performed through checklists, it is also believed that the developed method is suitable for the majority of owner's consultants and SME of the construction sector, where resource shortage for project planning and scheduling can lead to the development of low quality schedules.

In opposition to the legal connotation of existing Schedule Health Assessment methods, which mainly aim at performing schedule quality assessment for contract management purposes, the proposed method has been developed also to be used as a guide for the scheduling process. Further research is needed in this direction, as a proof of the proposed concept, by multiple project schedules testing.

The proposed method has a strong connotation in the construction sector, or it is construction oriented, while indeed most of existing standards are not. In fact the second indicator, construction process requirements, aims at developing a process-oriented project schedule, conforming the schedule to the execution of project work on-site. Particularly, the detailed requirements concerning safety and workflow are believed to be very important, especially in the evaluated sample case of a network-based schedule, with the objective of conforming network logic and activity durations to the need of production in the building site without a formally defined Location Breakdown Structure. This is a well-known gap of network-based schedule, but it is believed that the generalization of good practices like Schedule Health Assessment can bridge between process needs and scheduling method.

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Appendix 1

Table A1 General requirements

Schedule Health Indicator	Requirements	Detailed requirements
General requirements	Schedule process procedure	<ol style="list-style-type: none"> 1. Project calendars identification 2. Activity coding structure 3. Main subcontractors participation 4. Standardized sched. procedure
	Schedule definition	<ol style="list-style-type: none"> 5. Milestones 6. Project duration 7. Master schedule & Critical path id. 8. Schedule logic integration 9. Realistic network logic
	Activity definition	<ol style="list-style-type: none"> 10. Activity easy to monitor 11. Total number of activity manag. 12. Activity duration reasonable 13. Activity name understandable 14. Total scope as defined by WBS 15. Submission date 16. Responsibility assignment 17. Special activities included

Table A2 Construction process requirements

Schedule Health Indicator	Requirements	Detailed requirements
Construction process requirements	Activity sequencing & structure	<ol style="list-style-type: none"> 18. Reasonable activity sequencing 19. Network logic used for all activities 20. Predecessor relation indicated
	Activity duration	<ol style="list-style-type: none"> 21. Duration definition 22. Duration estimation 23. Continuity of production
	Activity timing	<ol style="list-style-type: none"> 24. Weather sensitive activities 25. Building enclosure dependencies
	Construction process safety and productivity	<ol style="list-style-type: none"> 26. Work continuity 27. Work-flow 28. Safe & non-congested work areas

Table A3 Schedule mechanics requirements

Schedule Health Indicator	Requirements	Detailed requirements
Schedule mechanics requirements	Network and logic	29. Open ended activities
		30. Summary tasks logic
		31. Missing logic
		32. Relationship ratio
		33. Relationship types
		34. High duration
	Critical path	35. Critical path & critical activities
		36. Critical activities features
		37. Multiple critical paths
		38. Critical path test
		39. Critical path length index (CPLI)
	Float	40. Critical path logic
		41. Schedule criticality rate
		42. Near criticality rate
		43. Critical activity duration
		44. Float computation
	Soft & hard constraints, buffers	45. Reasonable float dimensions
		46. Excessive total float
		47. Negative float
		48. ASAP & ALAP computation
		49. Constraints
	Activity misassignments	50. Number of constraints
		51. Buffers
		52. No activity mis-assignments
		53. No empty milestones
		54. Number of lags
	Lag & lead (negative lag)	55. No leads

Table A4 Cost and resources requirements

Schedule Health Indicator	Requirements	Detailed requirements
Cost and resources requirements	Monetary value/cost of activities	56. Monetary value of activities
		57. Total monetary value
		58. Progress payment
	Project cost ratio	59. Project cost ratio range
	Resource-loaded activities	60. Resource loading
		61. Resource productivity
		62. Resource conflicts
	Project total level of effort	63. Total amount working hours/days
		64. Project effort ratio

Table A5 Control process requirements

Schedule Health Indicator	Requirements	Detailed requirements
Control process Requirements	Activity progress evaluation	65. Percentage complete 66. Schedule slippage
	Schedule review and baseline	67. Schedule maintenance 68. Actual progress 69. Variance report 70. Baseline Execution Index
	Schedule projections	71. Schedule projections 72. Corrective actions
	Invalid dates and missed tasks	73. Invalid dates 74. Missed tasks 75. Out of sequence

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